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by

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PREFACE

Development of new engineering equipment is more often then not impeded by lack of suitable material with physical properties capable of fulfilling the rigid requirements imposed by the new advanced designs. The construction of power equipment, in particular, would benefit greatly if new alloys were made available that would allow the use of higher temperatures and yet retain their strength and creep resistance under high stresses.

This challenge has not gone unheeded for great strides have been made in recent years in developing heat and creep resisting alloys, but mainly by the tedious process of "trial and error". A knowledge of the basic facts underlying the phenomena of creep would offer a means by which a more positive and direct approach could be made.

The fundamental study of creep phenomena has been pursued by increasing numbers of investigators and many theories have been offered to explain the mechanisms by which creep occurs. However, these theories, on the whole, were shown to be valid over narrow ranges of test variables. Their analysis is based on the assumption that creep is a thermal activation process in which one mechanism plays a predominant role. The expressions developed are found to be valid only in the high temperature region and under constant stress or load conditions. One of the most recent and successful

theories was proposed by Dorn and co-workers at the University of California in Berkeley, California, but is again limited to the high temperature regions.

An investigation of the creep phenomena over a greater range of temperatures extending into the "low temperature" regions might uncover new creep mechanisms which play an important role in the overall picture but have been overlooked in favor of those showing the predominating influence at high temperatures.

This investigation initiated such a program of study. Equipment and technique were developed to study the creep behavior of metals at low temperatures. Specifically, a study of the behavior of magnesium at low temperatures was started. It is believed that only by a study of the creep mechanisms when they exert a noticeable influence can each be isolated, and then finally their behaviors integrated into an overall explanation of the creep phenomena in metals, which would greatly clarify the many questions, as yet unanswered, in high temperature creep.

The writer wishes to express his thanks to Assistant Professor A. Goldberg of the U. S. Naval Postgraduate School for his encouragement and assistance in the preparation of this paper; and to the other members of the Department of Metallurgy and Chemistry, who made this investigation possible by their help and cooperation.

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TABLE OF SYMBOLS AND ABBREVIATIONS

N	Number of activated complexes passing a point P multiplied by their rate
ΔF	Free energy of activation per gram molecule
K	Boltzman's constant
h	Plank's constant
R	Gas constant
T	Absolute temperature in degrees Kelvin
A,B	Parameters
$\dot{\varepsilon}$	Strain rate
ΔH	Activation energy for creep
σ	Applied stress
θ	Temperature-compensated-time parameter
t	Time of Test
f	Function of-
$^{\circ}C$	Degrees Centigrade
ε	Strain
ε_t	Total Strain
ΔT	Temperature increment
σ_i	Initial stress

CHAPTER I

INTRODUCTION

Interest in the behavior of metals and alloys under high stress and widely varying temperatures has increased at least as rapidly as our modern technology. This stimulation of interest is in part, the natural outgrowth of the desire to keep step with the latest design requirements where alloys of high strength to weight ratio capable of withstanding plastic deformation under stress are sought. Short of a complete understanding of the phenomenon of time-dependent deformation, known as creep, it would be desireable to experimentally test metals in short time tests and be able to predict their behavior over a designed life time.

Many investigators have noted the similarity between certain creep phenomena and a chemical reaction where matter rearranges by surmounting potential barriers. Eyring, in his study of viscosity, plasticity, and diffusion of liquids, proposed a general reaction-rate equation which accounted for the activation energy required to maintain a reaction at a given rate [1,2,3].

$$N = \frac{KT}{h} e^{-\Delta F/RT} = A e^{-\Delta F/RT} \qquad (1)$$

Since creep is a rate process and temperature dependent, the rate equation (1) has been the basis for many of the existing creep theories having been modified by various investigators

to fit experimental data. Even in their modified forms, these equation were found to be valid over narrow ranges of test conditions.

Kauzmann[4] applied the reaction-rate theory to the plastic flow of metals which in a simplified form[5] is:

$$\dot{\varepsilon} = AT e^{-\Delta H/RT} e^{B\sigma} \qquad (2)$$

The equation was proposed by Kauzmann principally for the analysis of secondary creep rates with implications that A and ΔH would have the same values for all strain and temperature conditions in the secondary- creep range.

Andrade suggested that following an initial strain, two independent processes of metal flow existed, that of transient and quasi-viscous flow[6]. The Becker-Orowan and Mott-Nabarro theories for transient creep suggest that the activation energy should increase with strain[3]. The Kauzmann-Seitz thermal activation theories, on the other hand, suggest that the activation energy should decrease with increasing values of applied stress[3].

Zener and Holloman related the flow stress of metals to the temperature and strain rate when at the same state by the equation [3,8]:

$$\sigma \equiv \sigma(\dot{\varepsilon} e^{\Delta H/RT}) \qquad (3)$$

with the further implications that ΔH, the activation energy,

is independent of the state of the material.

Extensive studies have been made recently at the University of California Institute of Engineering Research, Berkeley, California by Dorn and co-workers[5,7,8,9,10] on creep of aluminum and its alloys and have met with considerable success in correlating their proposed theory with actual experimental data for high temperature creep. Dorn and Sherby[7] noted that the state of the material for a given stress was dependent only on the creep strain. This implied that the time axis of the strain-time curves could be modified so that curves at different temperatures would superimpose on one another.

Expression (3) may be written as:

$$\dot{\varepsilon} = e^{-\Delta H/RT} \cdot f(\sigma) \tag{4}$$

which for a constant temperature and stress* reduces to:

$$\varepsilon = te^{-\Delta H/RT} \cdot f(\sigma) \tag{5}$$

Thus by running two tests at two different temperatures under identical stress, the time to reach the same strain would be given by:

$$t_1 e^{-\Delta H/RT_1} = t_2 e^{-\Delta H/RT_2} \tag{6}$$

*Sherby, Orr and Dorn[10] show that equations (4) and (5) can also be used to correlate constant load creep and tensile data.

where subscripts "1" and "2" refer to the two different temperatures. From this we can solve for ΔH, the activation energy.

Dorn and co-workers[7,8,9] showed that for aluminum at high temperatures, ΔH was essentially constant and was independent of stress. A further observation was that the activation energy for high temperature creep was essentially the same as that for self-diffusion. The validity of these findings was substantiated after analyzing much of the available data in the field with similar conclusions. Further proof of this was shown when Sherby[12] used Roberts[13] experimental data on creep of magnesium-cerium alloys and obtained a constant ΔH at high temperatures which was that for self-diffusion.

The fact that at high temperatures ΔH, the activation energy, is essentially equal to the energy of self-diffusion suggests that high temperature creep arises primarily from a dislocation-climb process, other processes being negligible. Further observations were made indicating equation (6) fails at temperatures below those for rapid crystal recovery[8]. Reasons for this were attributed to two factors[7,11]:

1. Identical structures are not obtained under a given stress at a given θ or strain, ε, for low temperatures.

2. The rate controlling process at low temperatures might be attributed to thermal activation of dislocations over barriers, if this is the case the apparent activation energy should be linearly dependent on the applied stress.

That ΔH is constant in a particular temperature range does

not necessarily imply that there is only one process taking place but rather that one process is predominant. Thus, the success obtained from creep correlations at high temperatures might be considered as somewhat fortuitous in that variations of the ΔH arising from the roles played by the other processes are of negligible magnitude. Attempts at correlating high and low temperature creep have so far failed; thus while the expressions developed by Dorn et al imply that the state of the material is a function only of stress and strain in the high temperature region*, they showed that for low temperature the state of a material is also dependent upon the previous strain history. This suggests that at low temperatures the effects of different mechanisms are felt[5].

Tietz and Dorn[14] in a study of the creep behavior of copper at intermediate temperatures (348°K to 469°K) show that the creep correlations still hold in this range. Here, ΔH is practically constant but is lower then the energy of self-diffusion. This suggests that creep at this temperature may be due mainly to a different process then that for high temperature such as a dislocation-climb process or an atom-vacancy exchange.

A better understanding of the basic creep mechanism would most certainly increase the probability of success in the development of new alloys and the improvement of existing ones. Further knowledge of the creep behavior of metals at low temperature might expose a new facet in the mechanisms of the creep phenomena.

*For non-precipitating systems

The change of ΔH in the intermediate temperature range, the failure of the creep laws and the dependence on history at low temperatures must undoubtably be the result of other mechanisms playing an important part here in the deformation process. This suggests that the nature of the mechanisms which play a minor role at high temperatures might be brought out by low temperature studies.

This investigation initiates such a program of study. This thesis constitutes the preliminary work involving the design of equipment and the development of a testing technique. An initial study was made to determine the effect of stress, strain and temperature on ΔH of magnesium in the termperature range between ambient temperature and -78°.

SUMMARY

Equipment and techniques for the study of the behavior of metals at low temperature were developed. The activation energies for creep of magnesium at low temperatures and their variation with temperature, strain and stress were determined. The activation energies were obtained by the simple technique of rapidly varying temperature ($\Delta T = 10^{\circ}$ to $20^{\circ}C$) throughout a constant load creep test. At a given state and stress the following equation could be used to determine activation energies:

$$\dot{\varepsilon}_1 e^{\Delta H/RT_1} = \dot{\varepsilon}_2 e^{\Delta H/RT_2} \qquad (12)$$

The subscripts refer to the states immediately preceding and

immediately after a temperature change.

ΔH was found to vary with temperature but was essentially independent of stress or strain. ΔH was found to be about 16,600 $\pm$ 500 cal/mole at ambient temperature and decreased to about 9,000 $\pm$ 500 cal/mole at -78°C.

Determination of ΔH at these low temperatures by high temperature technique, namely by comparison of two identical load-creep curves at different temperatures, indicates that the structure is not only strain dependent but also temperature dependent. The high temperature creep correlations are based on the assumption that ΔH is constant and that structure is dependent only on the strain and load. Both of these factors were found to be untrue at low temperatures and this accounts, at least in part, for the failure of low and high temperature correlations.

CHAPTER II

EXPERIMENTAL TECHNIQUE

BASIS OF ANALYSIS

Sherby and Dorn[7,9,10] demonstrated that the creep strain, ε, is a function of the parameter, θ, for constant load where:

$$\theta = te^{-\Delta H/RT} \tag{7}$$

$$\varepsilon = f(\theta,\sigma) \tag{8}$$

holding σ constant and differentiating with respect to time we obtain:

$$\dot{\varepsilon} = \frac{\partial f}{\partial \theta}\frac{d\theta}{dt} = \frac{\partial f}{\partial \theta}(\theta,\sigma)e^{-\Delta H/RT} \tag{9}$$

$$\dot{\varepsilon}e^{\Delta H/RT} = \frac{\partial f}{\partial \theta}(\theta,\sigma) \tag{10}$$

but, for a given ε (given state), according to equation (8),

$$\dot{\varepsilon}e^{\Delta H/RT} = f_1(\sigma) \tag{11}$$

All external controllable variables during an isothermal creep test are kept constant, therefore the change in creep rate, is directly dependent upon the changes in the internal state of the metal accompanying the creep process. Success in the application of equation (6) is due to the attainment of identical states at a constant stress and a particular value of θ.

Therefore, if the states at two temperatures are identical and the stress is constant, equation (11) can be written as:

$$\dot{\varepsilon}_1 e^{\Delta H/RT_1} = \dot{\varepsilon}_2 e^{\Delta H/RT_2} \qquad (12)$$

where the subscripts "1" and "2" refer to the two test temperatures. The activation energy for creep can now be determined by the following simple technique which was first used by Tietz and Dorn[11].

A specimen is extended at constant load at a temperature, T_1, to a strain, ε . At this point the temperature is changed rapidly to T_2. The strain rates $\dot{\varepsilon}_1$, and $\dot{\varepsilon}_2$ at the two temperatures T_1 and T_2 extrapolated to ε may then be considered as being characteristic for the same state of the material, namely that developed at ε , at these respective temperatures. A true activation energy for creep at the given stress can now be obtained from equation (12).

This technique is based on the assumption that creep occurs by means of some thermal activation process, thus being valid

for any creep mechanism that depends on thermal activation. If the activation energy is in fact constant within the temperature range of variation T_1 to T_2, a true ΔH will be obtained; if not, this value will fall between the true values for ΔH at T_1 and T_2. An approach to the ΔH may then be obtained by using small temperature intervals.

Equation (12) can now be written as:

$$\Delta H = R \left(\text{ln.} \, \dot{\varepsilon}_1 / \dot{\varepsilon}_2\right) \left(\frac{T_1 T_2}{T_1 - T_2}\right) \qquad (13)$$

This technique is simple and practically assures a constant state with elimination of all know variables except temperature. Fig. 1 illustrates the principle schematically. Since only one sample is used to make several determinations of ΔH, variations due to the effects of sampling scatter are circumvented. However, the accuracy of the results are directly dependent on the accuracy of the temperature determination and the graphical determination of strain rates.

EXPERIMENTAL EQUIPMENT

The test equipment that was designed and built for this low temperature investigation is illustrated in Fig. 2 in which the components are identified.

A constant load-lever type creep testing machine was used. The lever arm was counter-balanced (with pulling tab and extensometer above the specimen in test position) by means of a lead weight moving on a screw extending from the front of the arm in

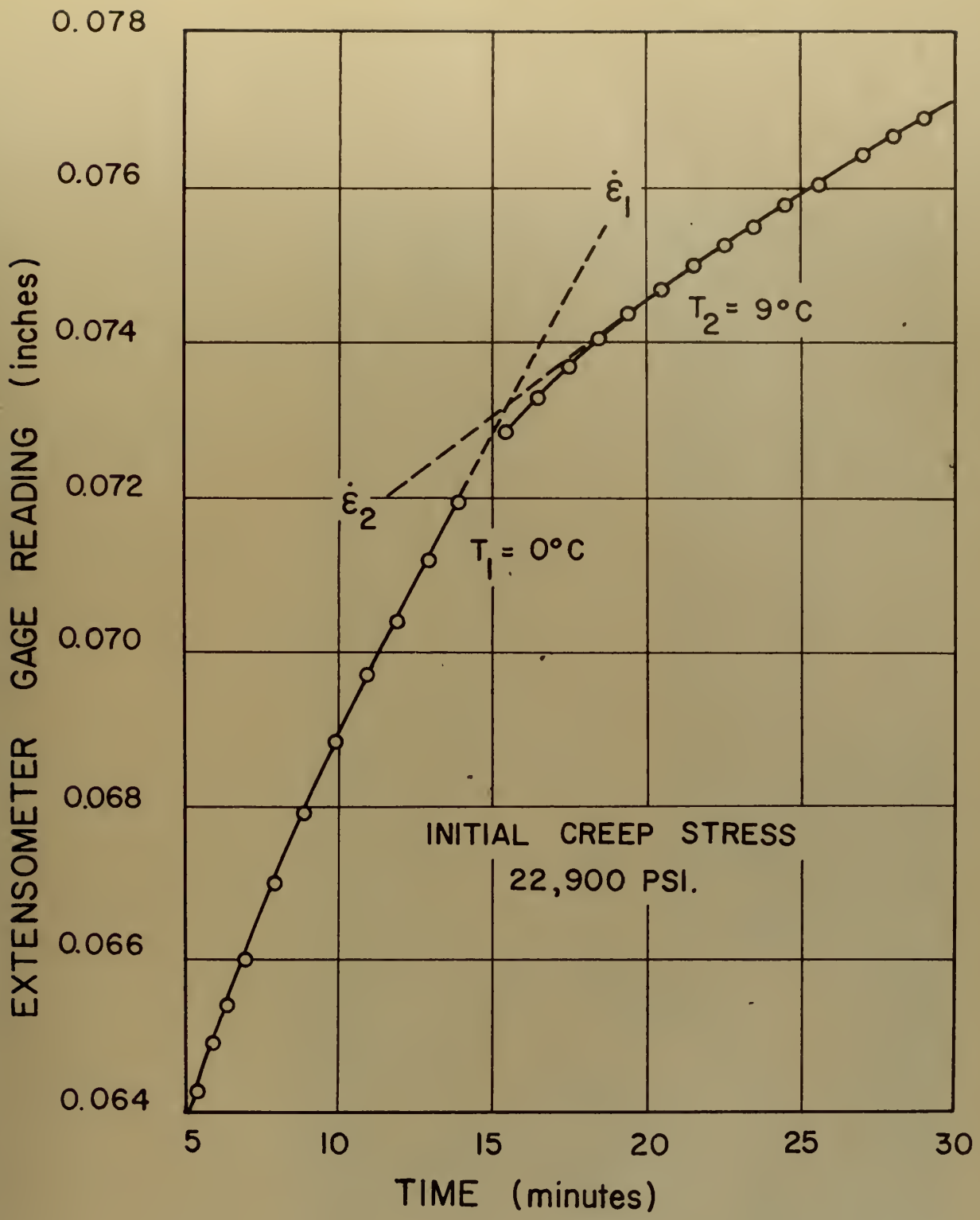

FIG. 1 CREEP CURVE SHOWING A TEMPERATURE CHANGE

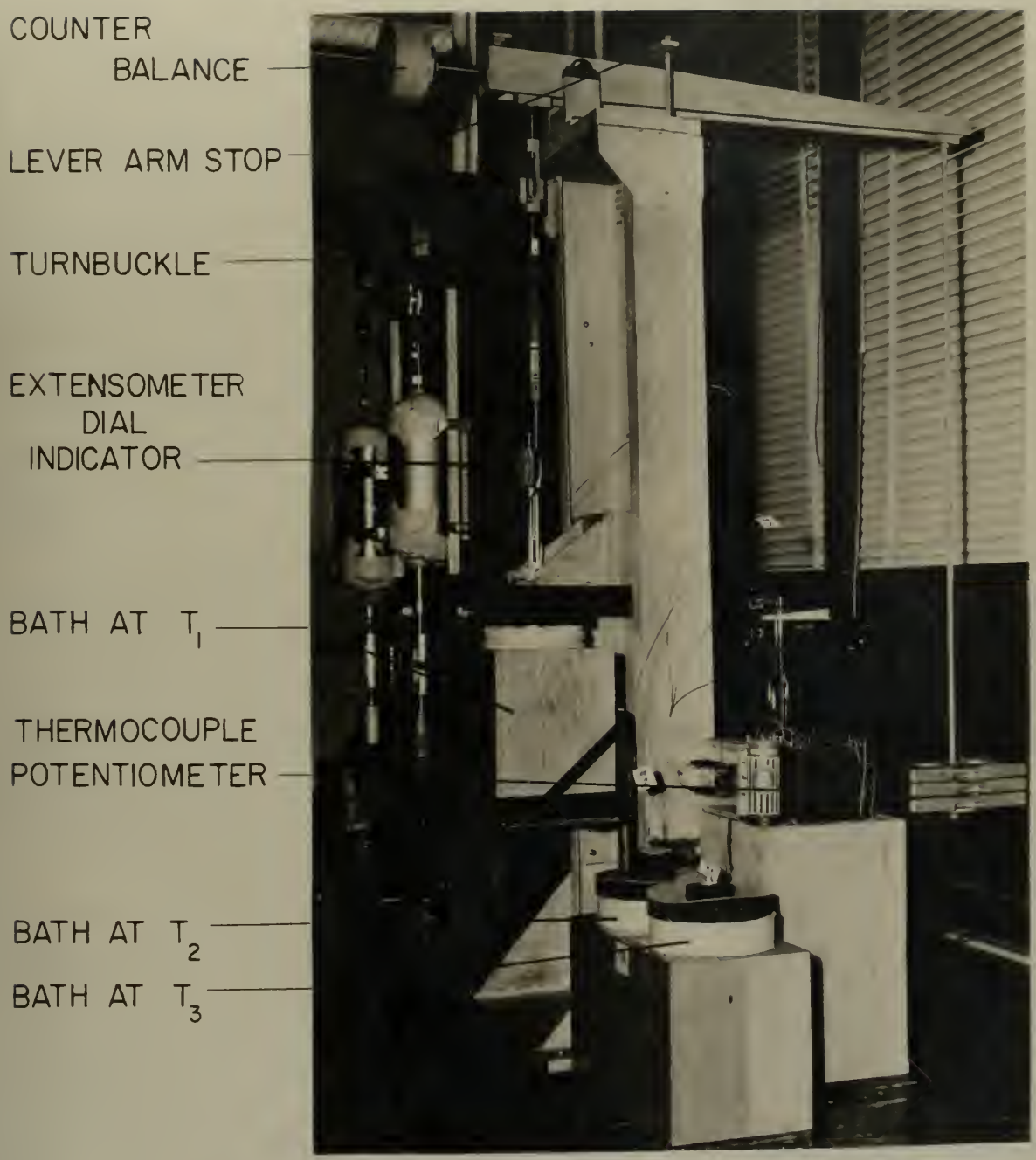

FIG. 2 CREEP TESTING MACHINE

line with the supporting knife edges.

Although the stress varied with the decreasing cross section of the specimen, each test was started with the lever arm in the same position as determined by the location of the lever arm stop. The exact lever arm ratio was determined by placing a Baldwin load cell in series with the pulling tab and checking the readings against calibrated weights used as the load. This ratio was 10.000 to 1 for any particular angle of the lever arm within its limiting positions. All points of suspension and balance were 60° - hardened knife edges to reduce any contact friction to a negligible value. Adjustment of initial lever angle was made with the turnbuckle which was in series with the pulling tab.

The specimen cage and extensometer, as shown in Fig. 3 and 4, were made of stainless steel so as to minimize thermal conductivity and yet retain strength and corrosion resistance. A lucite spacer thermally isolated the specimen cage from its supporting bracket by preventing metal to metal contact. Cork slab insulation was used to insulate the underside of the bracket while a shaped cork and felt pad sealed the opening around the extensometer. The lower specimen hook has a flexible pinned connection to the cage and is so designed as to allow removal and replacement of a specimen without removing the bath. Special baths were used in order to maintain necessary accuracy in the test temperatures. Since magnesium is highly sensitive to corrosive

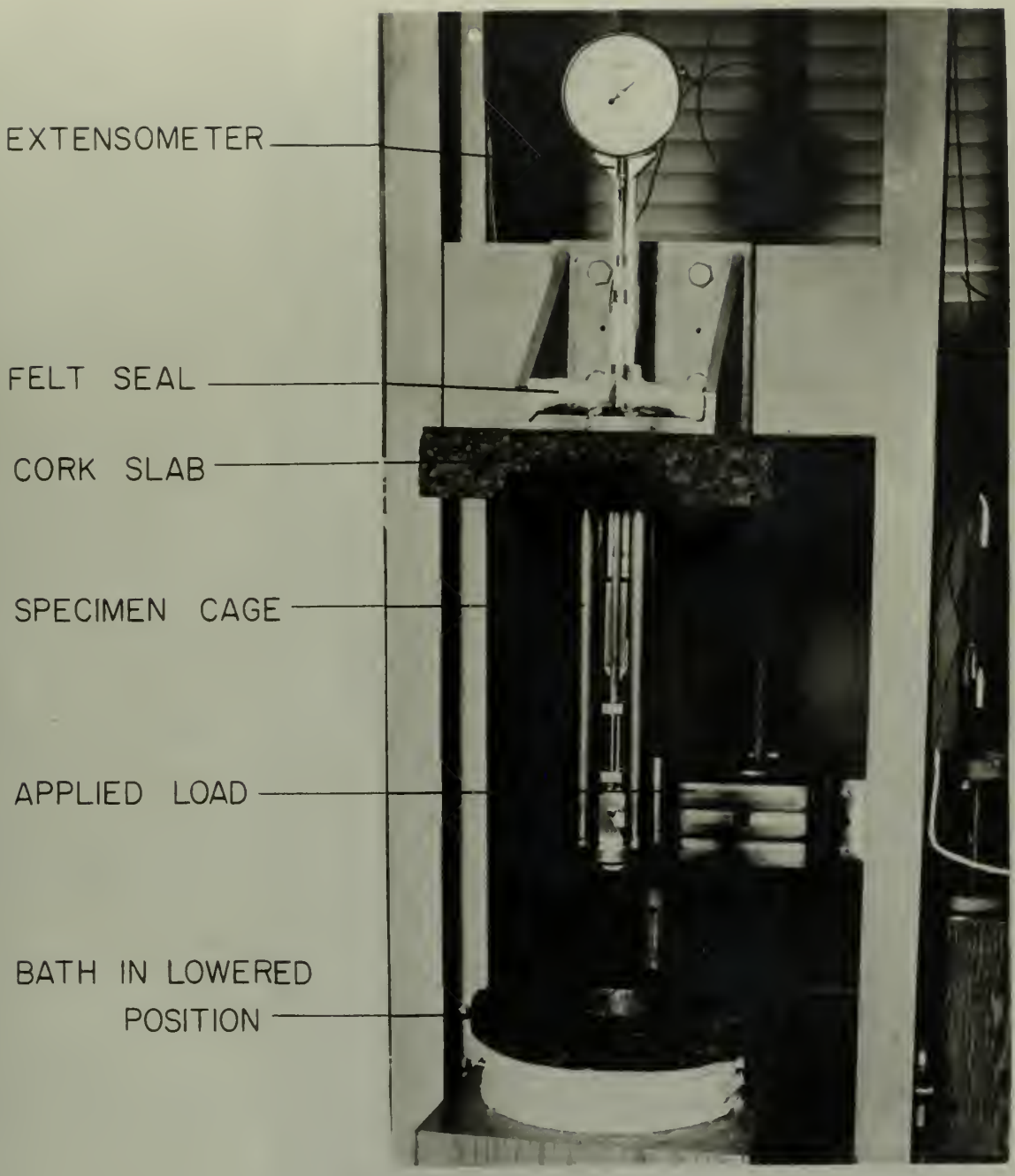

FIG. 3 SPECIMEN AND EXTENSOMETER IN TEST POSITION WITH BATH REMOVED

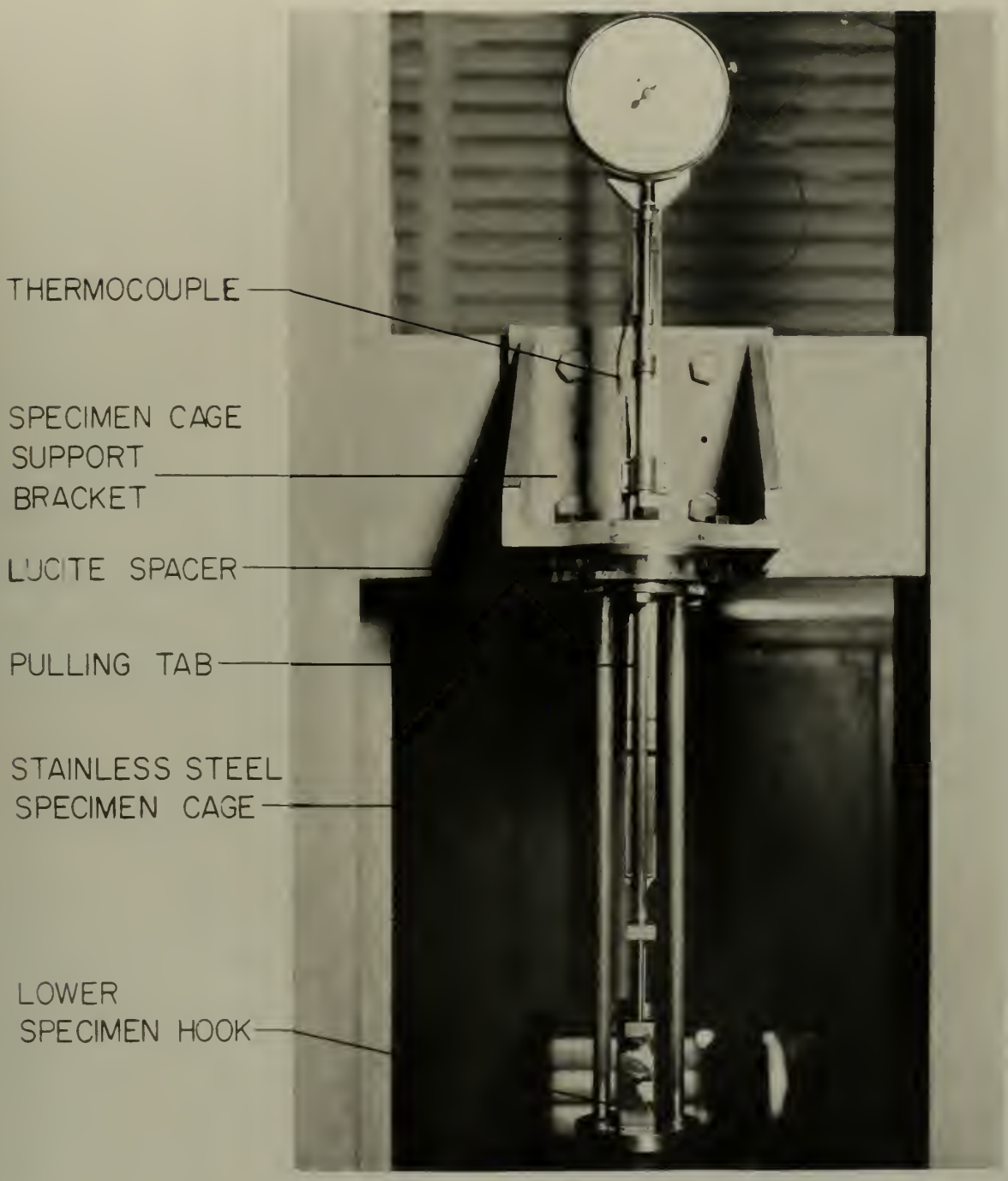

FIG. 4 DETAILS OF SPECIMEN CAGE

attack* especially under a stress, chemically neutral baths, which retained low viscosities at low temperatures[15], were used. A copper container was used to separate the bath from the frozen solutions as shown in Fig. 5.

The annular opening between the Dewar flask and the copper container was sealed and insulated by shaped cork. In the test position, the cork-slab facing and shaped cork were made to mate by sliding the bath-supporting platform upward into position which was then secured with a tapered pin. The baths used were pure mineral oil at 0°C to ambient temperature, special low viscosity silicone oil from 0°C to -55°C and Acetone from -55°C to -78°C.

Frozen solutions of eutectic composition were used to maintain constant temperatures[14]. A table of these appears in Appendix III. In each case the solutions were first chilled in a deep freeze. These were then frozen by adding solid carbon dioxide or liquid nitrogen. The solid solution was crushed and packed into the annular space between the copper container and the Dewar flask as shown in Fig. 5. The pack was sub-cooled by placing solid carbon dioxide or liquid nitrogen in the copper container. When the temperature was reduced sufficiently, the bath liquid was poured into the copper cup and allowed to stand until the arrest or eutectic temperature was attained. The specimen cage and extensometer were precooled prior to the start of a test by a separate bath; the test was started when the equilibrium temperature was reached. Temperature changes were made when

*Corrosion under stress appeared even in distilled water at 0°C

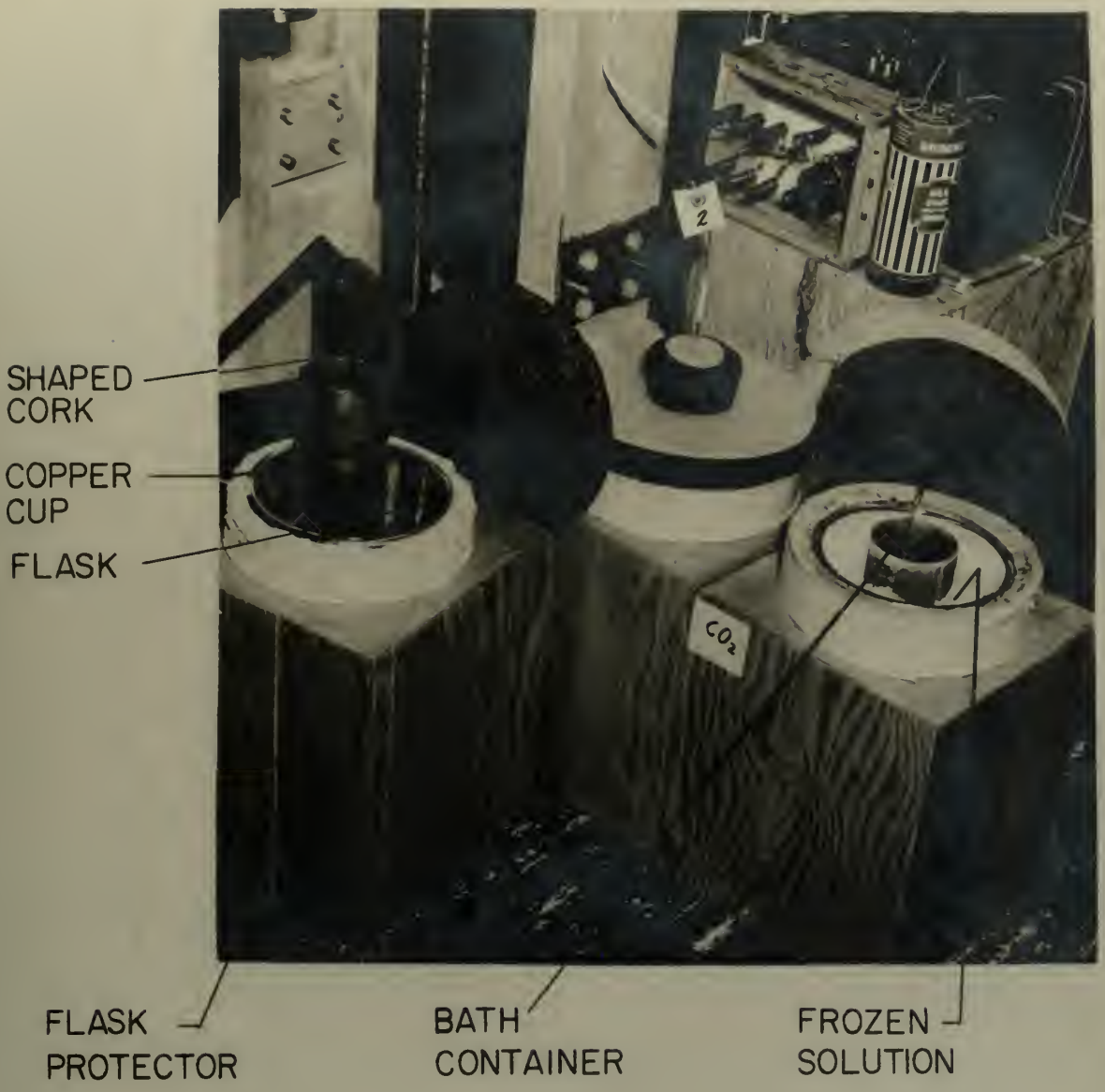

FIG. 5 COLD TEMPERATURE BATHS

a desired extension was reached or if the temperature varied from its equilibrium temperature by more than +0.4°C. Temperatures were taken by calibrated copper-constantan thermocouples which were in contact with the specimen within its gage length.

Creep strain rates were evaluated at the steady-state temperatures and extrapolated through the transient temperature range to the instant the temperature was changed as shown in the example illustrated in Appendix I. The time to reach a steady state was determined by obtaining time-temperature curves as shown in Fig. 6. From these curves and the experimental data, it was determined that the most reliable initial slope was that from three to five minutes after the temperature change.

Strain measurements were made by a mechanical extensometer as shown in Figs. 3, 4 and 7. The extensometer is of the concentric tube and rod type which actuated a 0.001 in. dial indicator. A calibration of the extensometer was made against an SR-4 strain gage, one of which was attached to each side of the specimen to check accuracy and the possibility of bending. Direct linearity within $\pm$ 0.0001 was exhibited and the reading sensitivity was judged to be 0.0002 in. A total elongation of one inch could be read before adjustment of the pulling tab length was required.

The two inch gage length was maintained while attaching the specimen to the extensometer by means of a spacer which was fitted between the two specimen blocks. One pin inserted in each

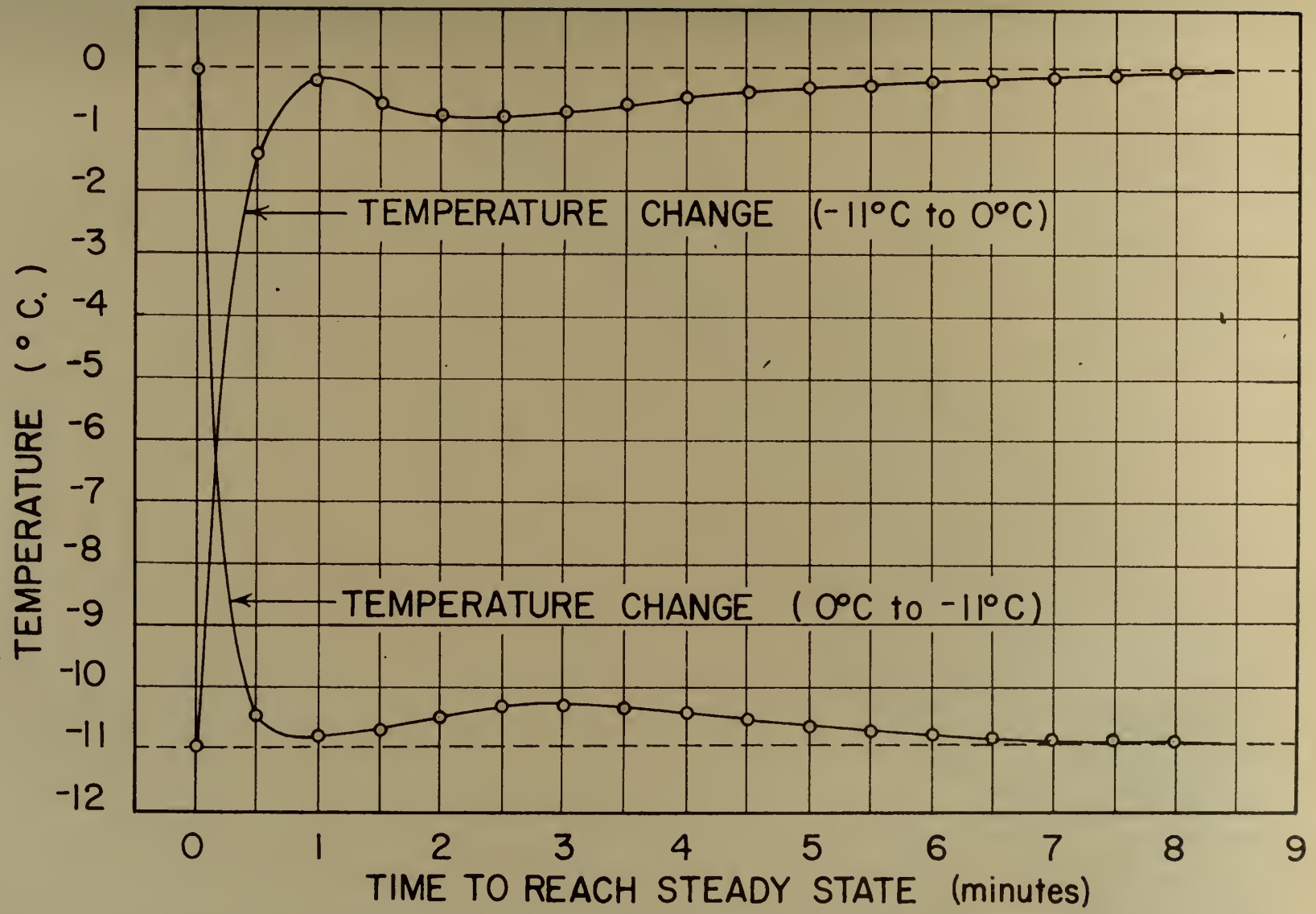

FIG. 6 VARIATIONS FOLLOWING SUDDEN TEMPERATURE CHANGES

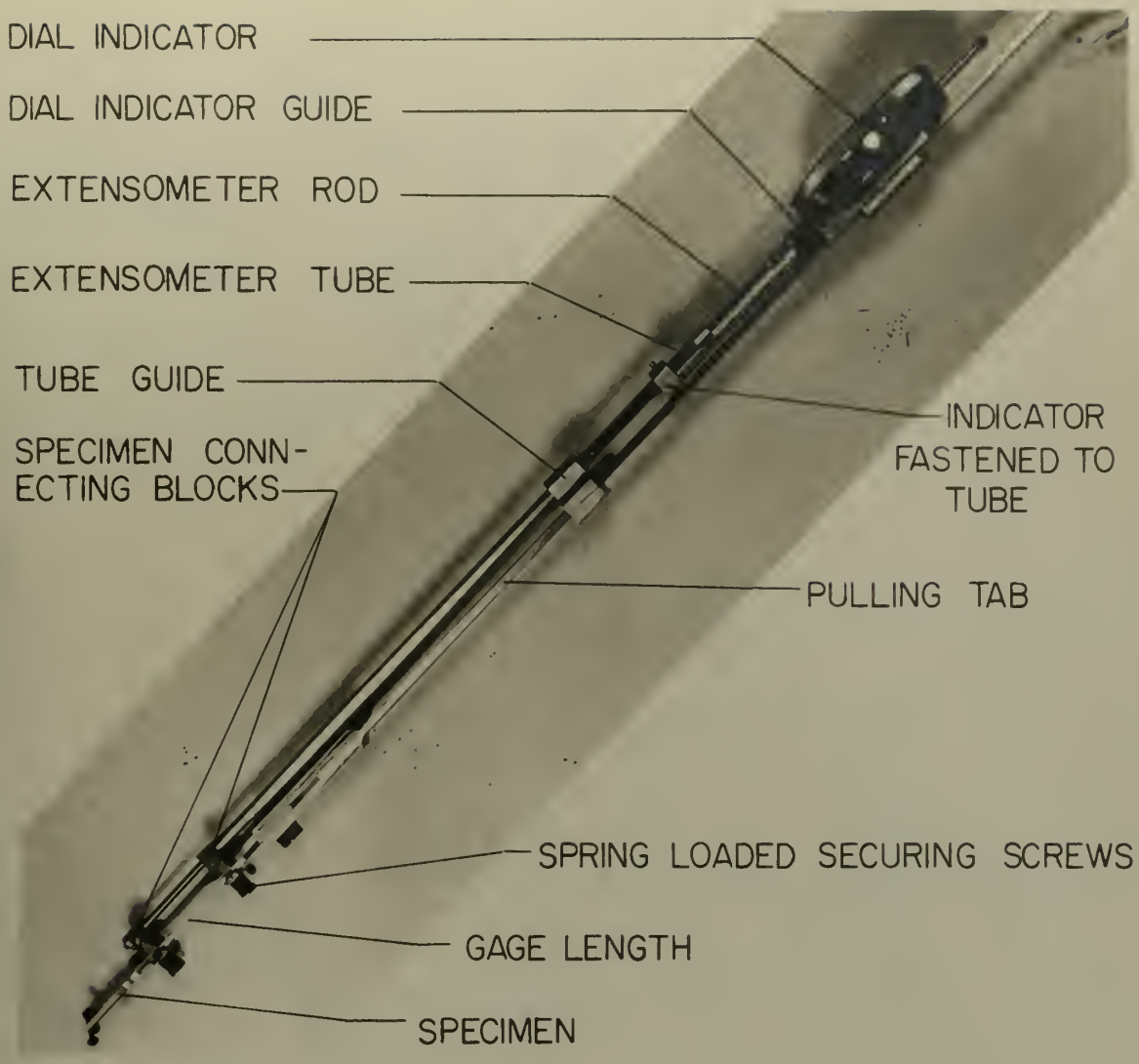

FIG. 7 DETAILS OF EXTENSOMETER

block with a 0.015 in. long protruding point held the specimen in its fixed position against a cap which was secured to the specimen blocks by two spring loaded screws.

TEST MATERIAL

Pure Magnesium (99.9%) extruded into (0.70x0.096x36 in.) bars furnished by the Dow Chemical Co. were used as the test material. The impurities are given in Table I.

Table I CHEMICAL ANALYSIS

Element	%	Element	%
Aluminum	0.012	Nickel	0.001
Calcium	$\leq$ 0.01	Lead	0.005
Copper	$\leq$ 0.001	Silicon	0.022
Iron	$\leq$ 0.001	Tin	$\leq$ 0.01
Manganese	$\leq$ 0.001	Zinc	0.052

Tensile creep specimens were machined from the 0.096 in. bars with their axes parallel to the extruding direction. Detailed dimensions are shown in Fig. 8. The central two inches of the specimen was the gage length.

Miscroscopic examination showed that the material as received was in the cold-worked state, with profuse twinning, the result of the extrusion process and machining. The average

grain diameter, which was obtained by averaging a number of linear counts across a section perpindicular to the tensile axis, was 0.0353 mm. The stresses were removed by annealing at a temperature of 300°C for one hour. Temperatures high enough to remove the twinning were not used since this resulted in duplexing and excessive grain growth.

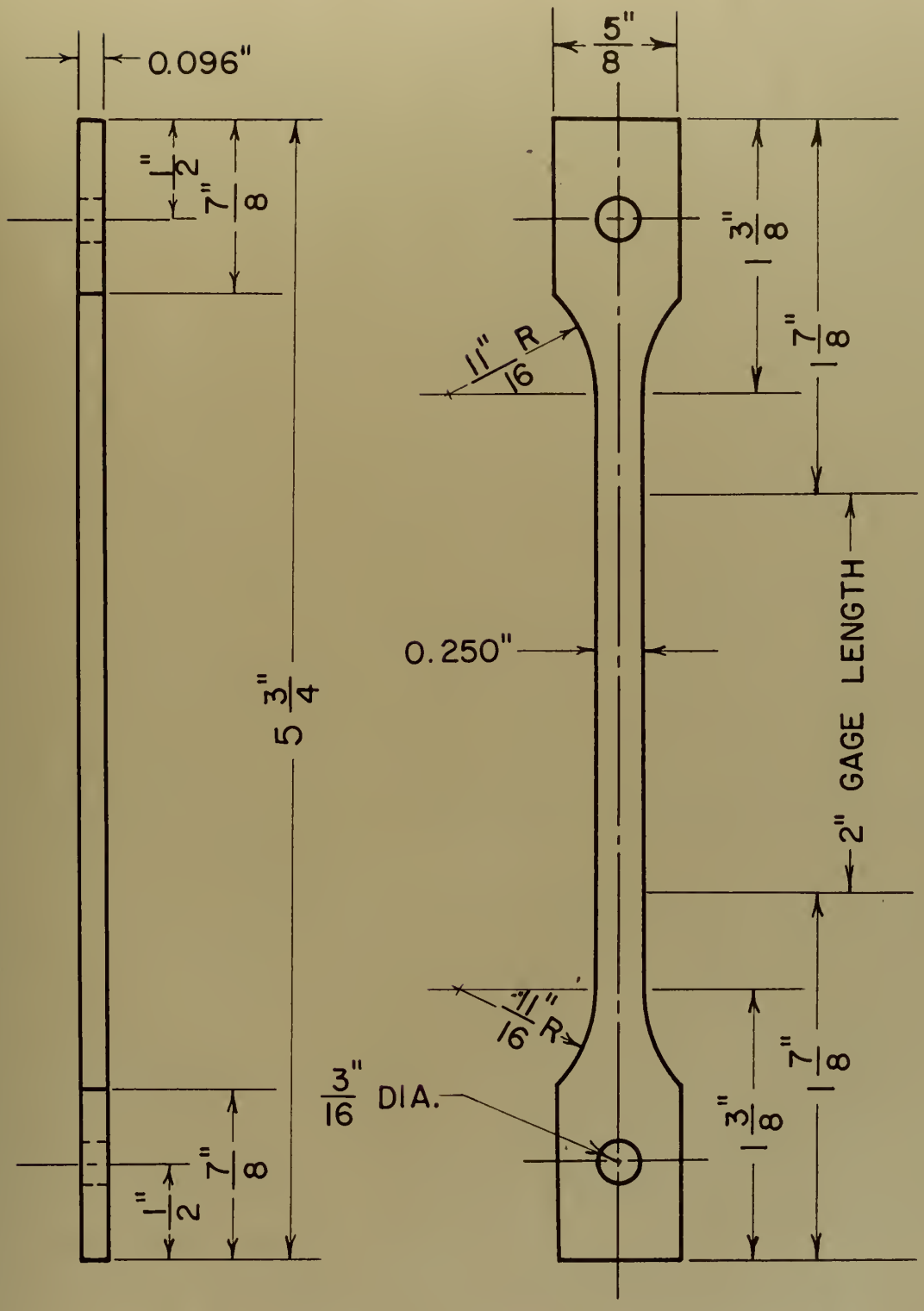

FIG. 8 TENSILE CREEP TEST SPECIMEN

CHAPTER III

ANALYSIS OF EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS

Creep rates, which were determined from the slopes of the original creep curves are illustrated in Fig. 1, and heats of activation, determined by equation (13), are listed in detail in Table 2 of Appendix II. Average values of ΔH for a particular initial stress and temperature variation (T_1 to T_2) are plotted in Fig. 9.

As a means of comparison, isothermal creep curves were obtained from tests at each of the temperatures used in the rapid variation of temperature technique at a constant initial stress of 25,000 psi. These curves appear in Appendix IV. A detailed list of creep rates and activation energies as determined from two curves at a given strain and the same load (which at high temperatures results in identical structures) are tabulated in Table 3 of Appendix II.

The data obtained from the temperature-variation technique show that ΔH for magnesium varies with temperature (almost linearly) from an average value of 16,600 $\pm$ 500 cal/mole at a mean temperature of 11.5°C to about 9000 $\pm$ 500 cal/mole at a mean temperature of -66.5°C. These values were essentially independent of stress from 18,000 psi to 27,000 psi and independent of strain up to fracture.

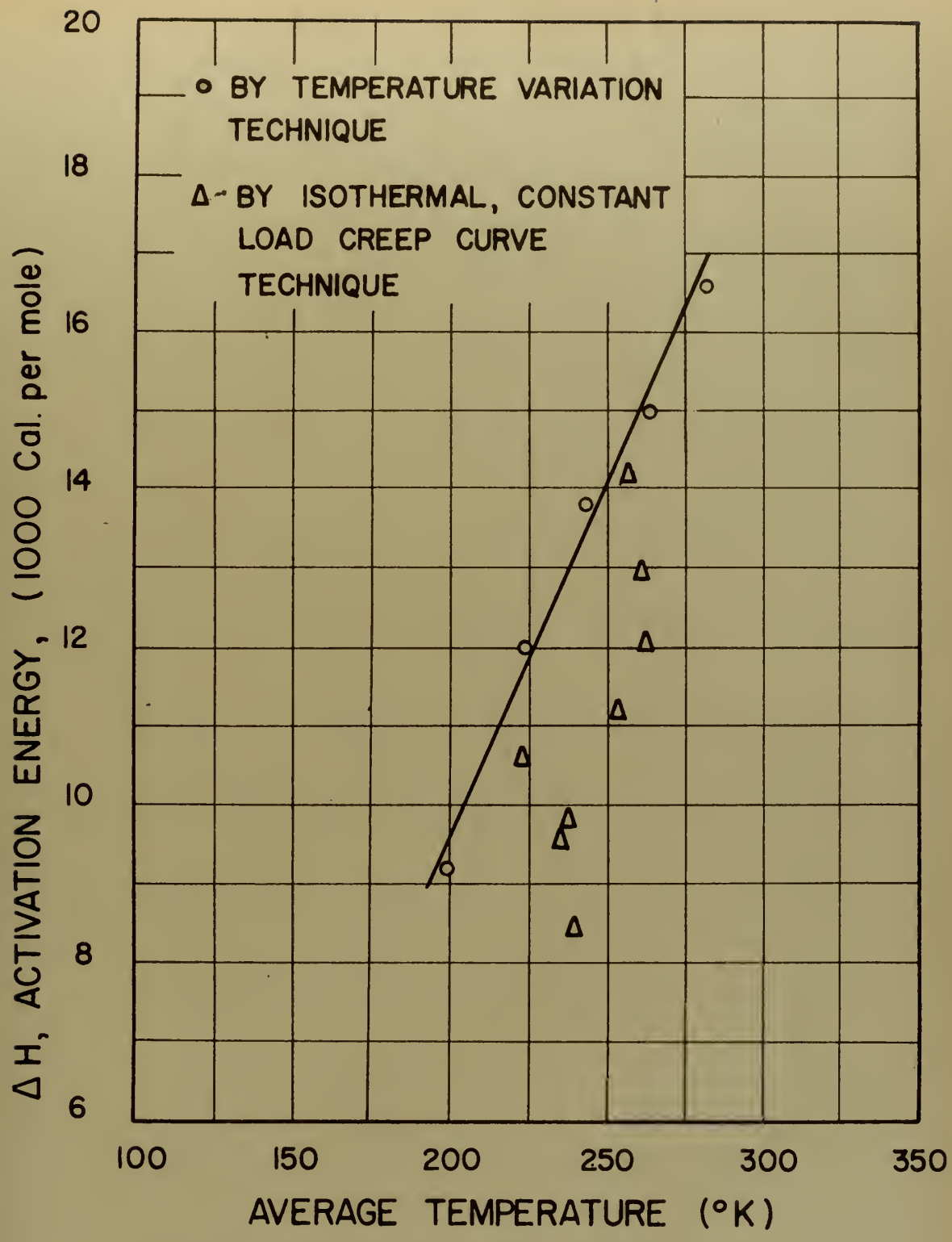

FIG. 9 ENERGY OF ACTIVATION AS A FUNCTION OF TEMPERATURE

Values of ΔH as obtained by both the isothermal creep curve and the temperature variation techniques were of the same magnitude. However, the values obtained by the former technique show considerable scatter.

DISCUSSION

The results obtained show that ΔH at low temperatures is temperature dependent, but independent of stress and strain. A constant ΔH is the correlation at high temperatures. Failure to obtain a satisfactory correlation between high and low temperature creep may be attributed, at least in part, to the variation of ΔH at low temperatures. The observation that ΔH is independent of stress and strain at low as well as high temperatures further justifies discarding the Becker-Orowan or Kauzmann-Seitz creep theories.

In the high temperature studies, the decreasing creep rates obtained during the course of isothermal creep at constant load were ascribed to structural changes; furthermore these changes were dependent only on stress and strain (independent of temperature). The creep rates obtained from the isothermal-constant load creep curves in this investigation showed a definite proportionality between adjacent curves at any given total strain (e.g. At T and T + 11°) which resulted in essentially a constant ΔH. Comparison of creep rates between any curves (say T and T + 22° or T + 11° and T + 22°) would again result in a reasonably constant ΔH. The values of activation energy for creep obtained at any one given total strain by an averaging process

did not coincide with the values obtained at the average temperature by the isothermal-constant load creep curve technique. (e.g. The average ΔH between T and T + 33° did not coincide with the ΔH computed between T + 11° and T + 22°). Furthermore, these values did not agree with the activation energies as obtained by the more exact temperature variation technique.

If we accept the validity of the results obtained by the rapid variation of temperature technique, and it appears reasonable to do so, then we must necessarily conclude that the values of ΔH obtained by the other technique are incorrect.

The failure would appear to be in the assumption of the structure being dependent only on strain and stress (valid at high temperatures). The constancy of ΔH obtained at a series of strains along a set of curves is probably due to a parallelism in the structural changes occuring at the two temperatures, the state of the metal at a given strain being dissimilar for different low temperatures. This substantiates the findings of Dorn, Goldberg and Tietz[5] that the mechanical equation of state is not valid at low temperatures. Here the plastic properties were found to depend upon the strain history of the metal (another factor in the failure in correlation between high and low temperature creep).

In the determination of activation energies for creep by the rapid variation of temperature technique, constant structure at two differing temperatures is assured by extrapolation of the strain rates back to the value of total strain at which the tem-

perature change was made. Therefore the variation in the activation energies obtained can be attributed to temperature changes alone since independence of strain and stress was also demonstrated.

CONCLUSIONS

1. Activation energie for creep of magnesium at low temperatures varies linearly with the temperature, implying that at least two processes take part in the creep mechanism whose relative importance depends on temperature.
2. Activation energies for creep appear to be independent of stress and strain for both low and high temperatures.
3. The failure to satisfactorily correlate high and low temperature creep is, at least in part, due to the two assumptions made for high temperature creep which fail at low temperature, namely:
    a. Constant ΔH
    b. State of the material is dependent only on stress and strain

EXPERIMENTAL ERRORS AND RECOMMENDATIONS

Since the degree of accuracy attained in this investigation was directly dependent on the ability to measure temperature closely and to obtain representative slopes from creep curves, the greatest improvement in experimental technique might be achieved through improved instrumentation. Temperature readings, particularly during the transient stage after a temperature change, could be better obtained by using a potentiometer accurate to 0.001 millivolt whose signal could be amplified and automatically plotted versus time by a Brush recorder. The time to reach a steady state temperature would be more accurately determined and a more representative initial slope after a temperature change would be obtained.

For example, an error due to a temperature rise of 0.4°C was accepted in this investigation. A 10.6°K change in temperature instead of an 11°K change from 273°K to 262°K would result in an error of 3.8% in the final computation of ΔH.

Because of the low creep rates for magnesium at low temperatures, the extensometer dial indicator used lacked the required accuracy. Figures in the fourth decimal place had to be considered as significant yet admittedly were dependent on a reading sensitivity of .0002". A dial indicator accurate to 0.0001" per 0.1" division with a reading sensitivity of 0.00002" should be used.

For these preliminary investigations a more ductile material at low temperatures (such as copper) could be used

which would permit greater creep rates without the likelihood of early failure. These rates could then be read more accurately from the creep curves. Temperature variation resulting in large creep rate ratios minimize the effect of experimental errors in reading slopes since in the computations, the natural log of the ratio is used.

Use of the same bath liquid throughout a range of temperatures is advisable. It is of primary importance that the bath liquid be chemically inert toward the specimen material but if there are any unknown surface effects, use of the same bath will produce like effects during each test resulting in better reproducability. It was found that acetone was the best liquid used since it was inert toward magnesium, retained low viscosity throughout the temperature range of the investigation and reached a steady state temperature rapidly.

The use of a metal which becomes brittle at low temperatures increases the problems resulting from notch sensitivity or the sensitivity to surface effects. Examination of the specimens in an optical comparator showed surface and machining defects which could have adverse effects on the results. Extreme care in final preparation of the surface is recommended for specimens used in the future, however, for these preliminary investigations, use of a more ductile material at low temperatures would be more practical. Larger values of creep rate would be had and surface effects would be lessened.

It was found that the use of subliming or boiling material

as the coolant for the low temperature baths was more satisfactory from the point of maintaining a constant temperature then the solutions of eutectic composition.

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APPENDIX I

ILLUSTRATIVE EXAMPLES

ΔH BY VARIATION OF TEMPERATURE TECHNIQUE

Refer to Fig. 10, which illustrates the method of obtaining representative steady state creep rates from a constant load-creep curve just prior to and just after a temperature change. $\dot{\varepsilon}_1$, the creep rate, is expressed throughout this report in inches per minute per two inch gage length since in the computation of ΔH the dimensionless ratio of strain rates is used.

At t = 90 min. and extensometer gage reading = 0.0571" the temperature was rapidly changed from $T_2 = 273^{\circ}K$ to $T_1 = 295.5^{\circ}K$.

The slope at t = 90 min. on the creep curve for $T_2 = 273^{\circ}K$ is 0.025 while the slope extrapolated back to t = 90 min., from t = 95 min. on creep curve for $T_1 = 295.5^{\circ}K$ is 0.250.

$T_2 = 273^{\circ}$ KELVIN

$T_1 = 295.5^{\circ}$ KELVIN

$\dot{\varepsilon}_2 = 0.025 \times 10^{-3}$ $\dfrac{\text{Inches}}{\text{Minute-2" Gage Length}}$

$\dot{\varepsilon}_1 = 0.250 \times 10^{-3}$ $\dfrac{\text{Inches}}{\text{Minute-2" Gage Length}}$

$R = 2$ Cal/Mole-$^{\circ}K$

$\dot{\varepsilon}_1 / \dot{\varepsilon}_2 = 10$

Solving for ΔH in equation (12),

$$\dot{\varepsilon}_1 e^{\Delta H/RT_1} = \dot{\varepsilon}_2 e^{\Delta H/RT_2} \qquad (12)$$

we get -

$$\Delta H = R \left(\text{In.} \frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2} \right) \left(\frac{T_1 T_2}{T_1 - T_2} \right) \qquad (13)$$

By substituting the experimental values -

$$\Delta H = 2 (\text{In. } 10) \left(\frac{273 \times 295.5}{22.5} \right) = 16{,}500 \ \text{Cal./Mole}$$

(for an average temperature 284.25°K)

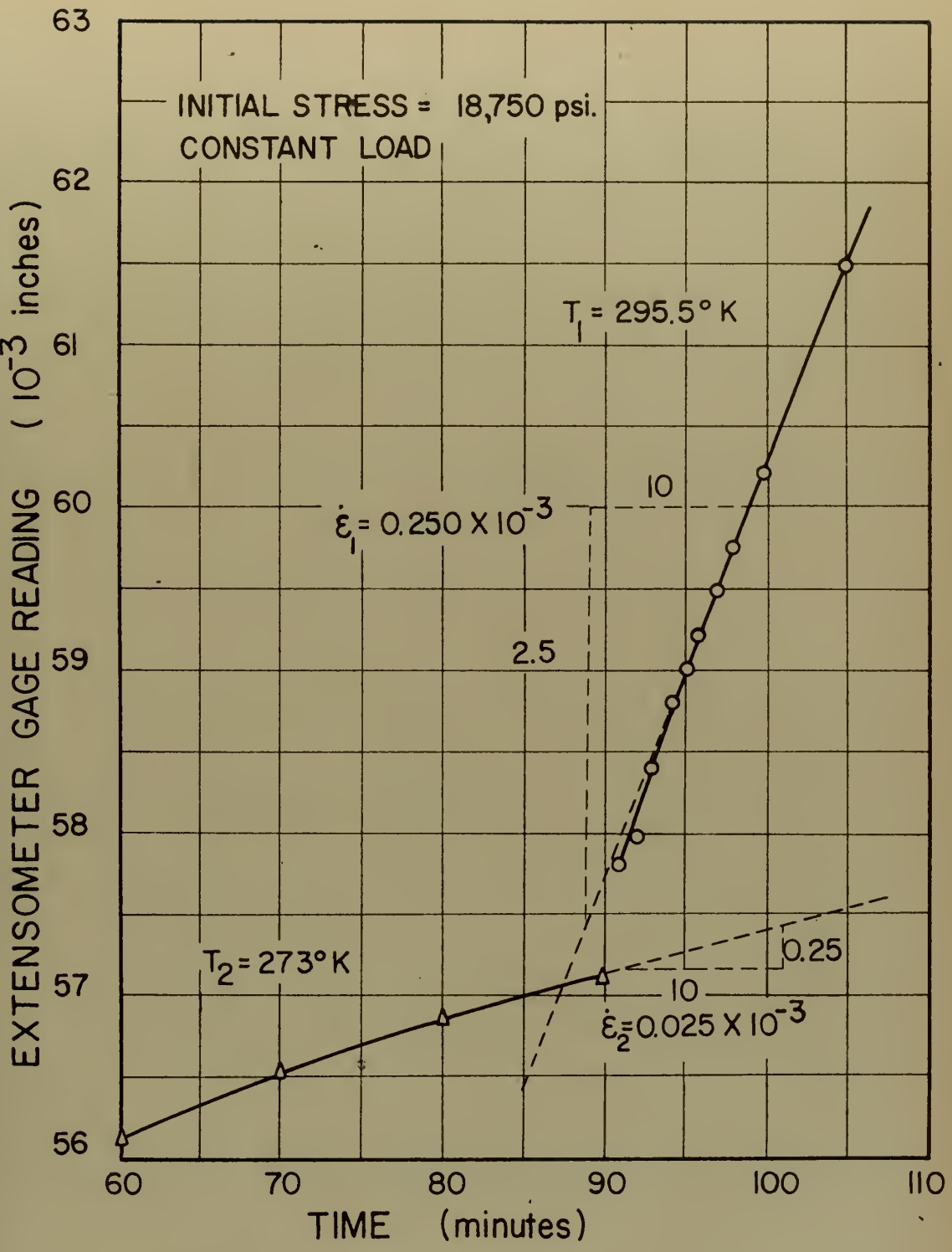

FIG. 10 ΔH BY VARIATION OF TEMPERATURE TECHNIQUE

ΔH BY THE ISOTHERMAL-CONSTANT LOAD CREEP CURVE TECHNIQUE

Refer to Fig. 11, which illustrates the method of obtaining creep rates from two different isothermal-constant load creep curves at a given strain.

The structure, at the states where the two creep rates are determined, is considered the same for high temperature creep.

If this assumption is also valid for low temperatures then equation (13) may be used to determine ΔH.

$T_1 = 273°$ KELVIN

$T_2 = 262°$ KELVIN

$\dot{\varepsilon}_1 = 0.95 \times 10^{-3} \ \frac{\text{Inches}}{\text{Minute - 2" Gage Length}}$

$\dot{\varepsilon}_2 = 0.38 \times 10^{-3} \ \frac{\text{Inches}}{\text{Minute - 2" Gage Length}}$

$\dot{\varepsilon}_1 / \dot{\varepsilon}_2 = 2.5$

$R = 2 \ \frac{\text{Cal.}}{\text{Mole - °K}}$

$$\Delta H = R \left(\text{In.} \ \dot{\varepsilon}_1 / \dot{\varepsilon}_2 \right) \left(\frac{T_1 T_2}{T_1 - T_2} \right) \qquad (13)$$

By substituting in the experimental values:

$$\Delta H = 2(\ln 2.5)\left(\frac{273 \times 262}{11}\right) = 11{,}900 \ {}^{Cal.}/_{Mole} \qquad (13)$$

(at an average temperature of 267.5°K)

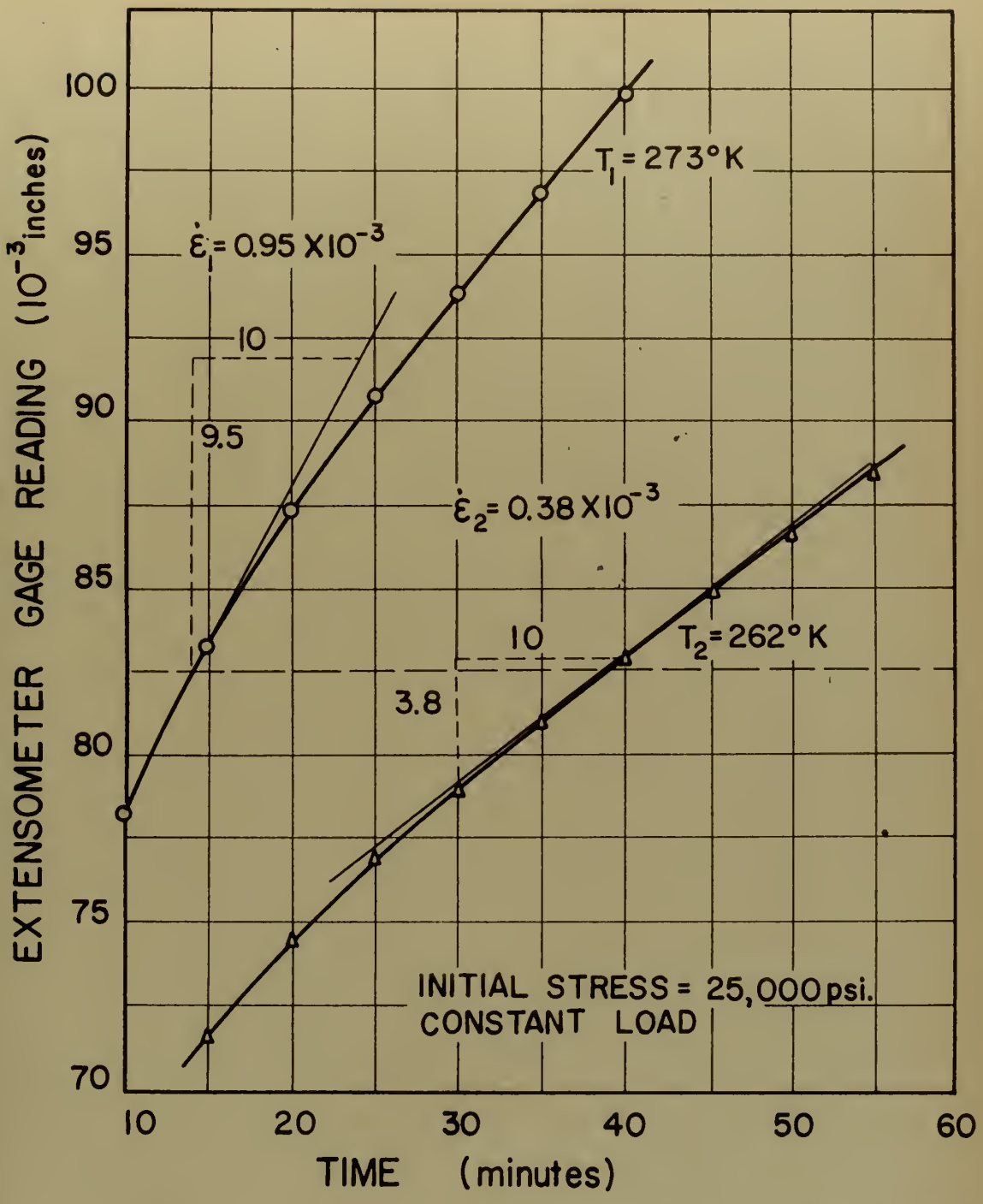

FIG. 11 ΔH BY THE ISOTHERMAL-CONSTANT LOAD CREEP CURVE TECHNIQUE

APPENDIX II

TABULATION OF RESULTS

TABLE 2

ΔH BY THE INSTANTANEOUS TEMPERATURE VARIATION TECHNIQUE

STRESS P.S.I. σ	TEMPERATURE °KELVIN T_1	T_2	STRAIN RATE PER 2 in. GAGE LENGTH PER MINUTE $\dot{\varepsilon}_1$	$\dot{\varepsilon}_2$	STRAIN RATIO $\dot{\varepsilon}_1/\dot{\varepsilon}_2$	TOTAL GAGE READING INCHES ε_t	TIME OF CHANGE MIN. t	HEAT OF ACTIVATION CAL/MOLE ΔH
18 750	295	273	0.72	0.08	9	54	15	16 100
	295.5	273	0.250	0.0250	10	57.1	90	16 500
	296	273	0.250	0.0250	10	72.3	150	16 200
	296	273	0.250	0.0250	10	73.2	255	16 200
	296	273	0.250	0.0250	10	87.4	350	16 200
	296	273	0.20	0.020	10	100	565	16 200
	296	273	0.14	0.0140	10	104.8	1530	16 200
	295.5	273	0.14	0.0140	10	114.9	1715	16 500
20 850	296	273	1.56	0.144	10.8	70.4	10	16 700
	296	273	0.86	0.084	10.3	76	65	16 400
	295	273	0.66	0.070	9.5	90	83	16 500
	296	273	0.55	0.050	11	93	135	16 800
	296	273	0.42	0.040	10.5	109	170	16 500
	296	273	0.37	0.035	10.6	111.2	240	16 550
	296	273	0.32	0.031	10.3	125.6	280	16 400
22 900	295	273	1.98	0.20	9.9	85	5	16 800
	295	273	1.25	0.13	9.65	96	32	16 600
	295	273	1.1	0.11	10	121	46	16 850
25 000	294.5	273	22.2	2.2	9.9	100	1.66	17 100
	294.5	273	9.9	1.1	9	127	14	16 500
	294.5	273	8.3	0.83	10	149	20.5	17 200
20 850	273	263	0.42	0.15	2.8	53.4	15	14 800
	273	264.5	0.14	0.06	2.33	91	95	14 400
	273	264.7	0.07	0.03	2.33	74.3	255	14 750
	273	265	0.058	0.025	2.32	77.2	345	15 200
	273	265	0.035	0.015	2.33	93.95	747	15 250
22 900	273	263	0.70	0.26	2.69	71.9	14	14 200
	273	263.5	0.34	0.12	2.67	83.9	65	14 850
	273	263.5	0.265	0.10	2.65	91	95	14 750
	273	263.5	0.24	0.09	2.67	95.2	130	14 850
	273	264	0.175	0.07	2.5	109.2	213	14 700
25 000	273	267	0.85	0.47	1.80	101.2	23	14 300
	273	267	0.74	0.40	1.85	115.1	42	14 850
	273	267	0.66	0.36	1.83	127.3	70	14 700
	273	267	0.60	0.325	1.84	141.9	95	14 850
22 900	246.2	232.7	0.90	0.16	5.6	30	10	14 600
	246.2	232.7	0.29	0.058	5	67.8	55	13 700
	246.2	232.7	0.25	0.05	5	78.3	100	13 700
	246.2	232.7	0.16	0.031	5.16	84.4	160	14 000
	246.2	232.7	0.16	0.031	5.16	86.3	200	14 000
25 000	241	233.5	0.81	0.33	2.45	70	6	13 450
	241	233.5	0.42	0.17	2.47	77.05	23	13 600
	241	234	0.28	0.12	2.35	94.9	103	13 650
	241	234	0.28	0.115	2.43	105.4	143	14 300
25 000	228	218	0.21	0.06	3.5	54	13	12 450
	228	218	0.12	0.039	3.08	55.8	53	11 200
	228	218	0.056	0.016	3.5	59.8	103	12 450
	228	218	0.027	0.0081	3.33	60.6	173	12 000
	228	218	0.021	0.006	3.5	61.8	233	12 450
27 100	228	218	0.225	0.0715	3.15	66.85	40	11 400
	228	218	0.135	0.040	3.37	71	65	12 100
	228	218	0.125	0.036	3.47	74.7	145	12 400
27 100	218	195	0.30	0.03	10	59	15	8 550
	218	195	0.11	0.01	11	58.7	50	8 860
	218	195	0.09	0.008	11.3	61.95	80	9 960
25 000	218	195	0.30	0.021	14.3	22	40	9 830
	218	195	0.10	0.009	11.1	69	48	8 900
	218	195	0.03	0.0025	12	114	47.4	9 150

TABLE 3

ΔH BY COMPARISON OF TWO ISOTHERMAL IDENTICAL LOAD CREEP CURVES

INITIAL STRESS (24,000 psi)

TEMPERATURE °KELVIN		STRAIN RATE PER 2 in. GAGE LENGTH PER MINUTE		STRAIN RATIO	TOTAL GAGE READING INCHES	HEAT OF ACTIVATION CAL/MOLE	AVE. TEMP °C
T_1	T_2	$\dot{\varepsilon}_1$	$\dot{\varepsilon}_2$	$\dot{\varepsilon}_1/\dot{\varepsilon}_2$	ε_1	ΔH	
273	262	1.6	0.65	2.48	70	11 800	- 5.5
273	262	1.4	0.55	2.53	75	12 250	
273	262	1.0	0.4	2.5	80	11 900	
273	262	0.96	0.37	2.51	85	12 050	
273	262	0.70	0.32	2.19	90	10 200	
273	251	1.6	0.20	8	70	12 950	-11
273	251	1.4	0.165	8.5	75	13 350	
273	251	1.0	0.12	8.4	80	13 250	
273	251	0.96	0.11	8.7	85	13 500	
273	251	0.70	0.10	7	90	12 150	
262	251	0.65	0.2	3.25	70	14 050	-16.5
262	251	0.55	0.165	3.33	75	14 400	
262	251	0.40	0.12	3.33	80	14 400	-16.5
262	251	0.37	0.11	3.36	85	14 450	
262	251	0.32	0.10	3.2	90	13 900	
273	229	1.6	0.04	40	70	11 550	-22
251	229	0.6	0.12	5	60	8 340	-33
251	229	0.27	0.6	4.85	65	8 240	
251	229	0.2	0.04	5	70	8 430	
262	229	0.65	0.04	16	70	9 700	-37.5
251	218	0.6	0.033	18.2	60	9 630	-38.5
229	218	0.42	0.12	3.58	55	11 580	-49.5
229	218	0.12	0.033	3.64	60	11 720	

APPENDIX III

COLD TEMPERATURE BATHS

SUBSTANCE	EUTECTIC MIX	FREEZE POINT	COMMENTS
% Anhydrous Salt Unless Otherwise States	% Salt or Solute with H_2O	Unless Otherwise States °C	
Distilled H_2O	$H_2O(S) + H_2O$	0°	
$Na_2S_2O_3 \cdot 5H_2O$	30.0	-11°	
$NaCl \cdot 2H_2O$	22.4	-21.2°	
NaCl	23.1	-22.4°	
Freon 12	-	-30°	Boiling Point
Linseed Oil	-	-34°	Melting Point
Freon 22	-	-40.6°	Boiling Point
Glycerol	67	-44.5°	
$CaCl_2$ $6H_2O$	58.8	-54.9°	
Alcohol-$CO_2(S)$	-	-72°	Liq - Solid Mix
Acetone-$CO_2(S)$	-	-78°	Liq - Solid Mix
Methyl Alcohol	-	-94.9°	Melting Point
Ethylene(C_2H_2)	-	-103.8°	Melting Point
Nitrogen	-	-195.8°	Boiling Point

APPENDIX IV

GRAPHICAL AND TABULAR PRESENTATION OF EXPERIMENTAL DATA

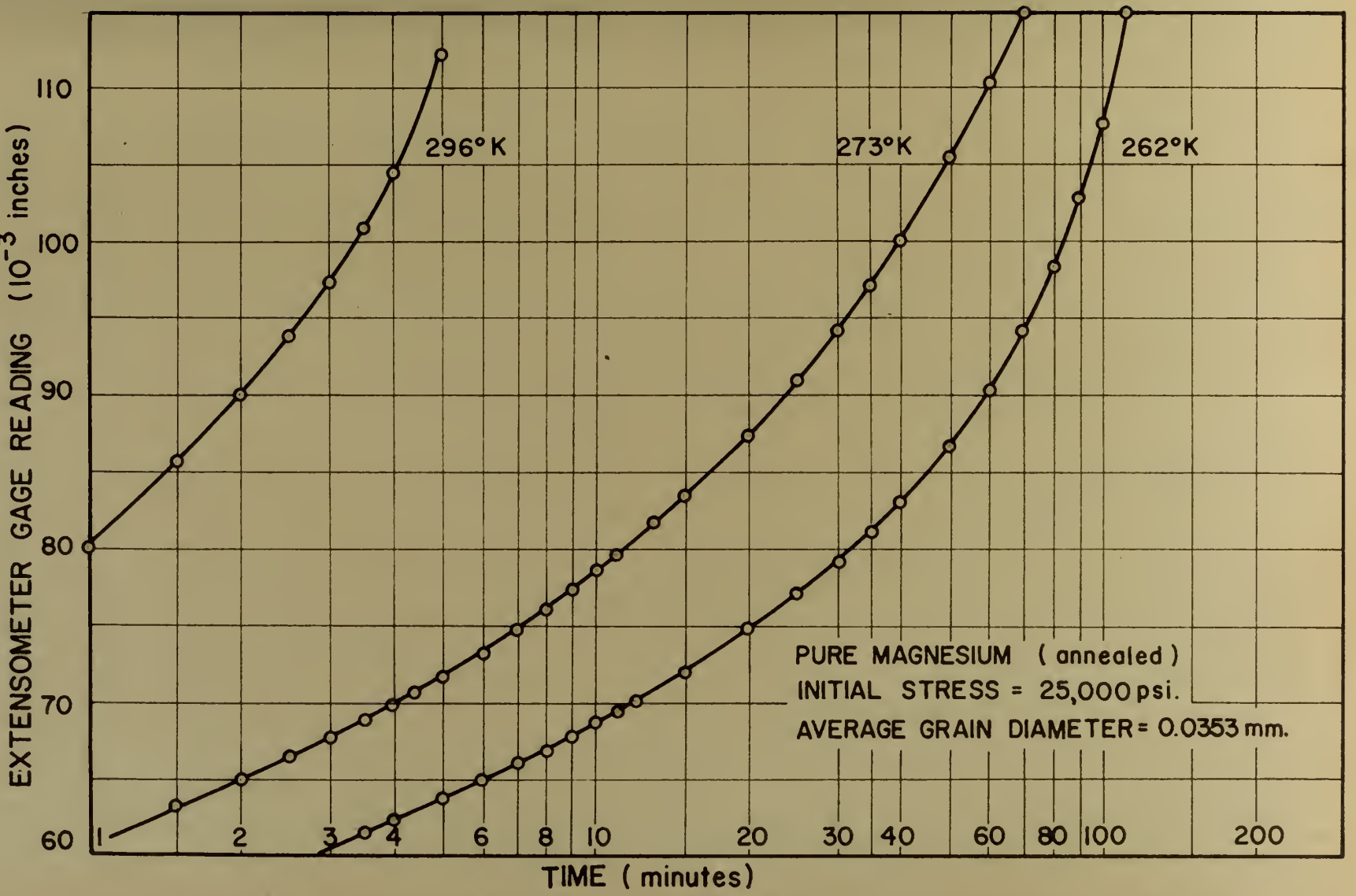

FIG. 12 ISOTHERMAL- CONSTANT LOAD CREEP CURVES

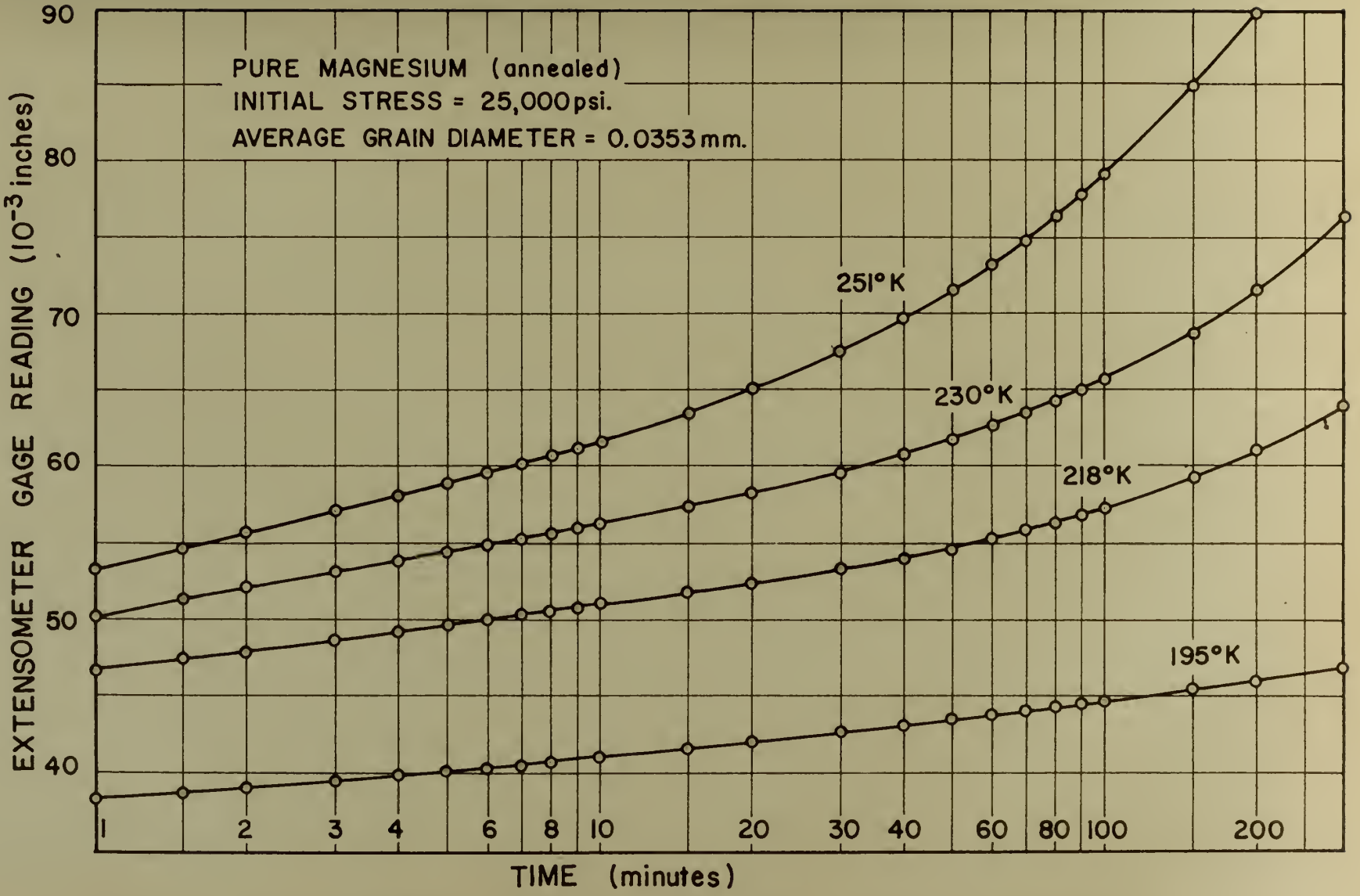

FIG. 13 ISOTHERMAL-CONSTANT LOAD CREEP CURVES

TABLE IV

EXPERIMENTAL DATA USING THE VARIATION OF TEMPERATURE TECHNIQUE

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPERATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
18 750	40.5	2	295
	42.6	3	
	44.3	4	
	45.7	5	
	46.9	6	
	48	7	
	49	8	
	50.5	10	
	51.2	11	
	51.9	12	
	52.6	13	
	53.3	14	
	54	15	295
	Change Temperature		
18 750	53.6	16	273
	53.9	17	
	54	18	
	54.1	20	
	54.2	22	
	54.3	24	
	54.5	25	
	54.9	30	
	55.1	35	
	55.3	40	
	56.6	70	
	56.7	75	
	56.9	80	
	57.0	85	
	57.1	90	273
	Change Temperature		
18 750	57.7	91	295.5
	58	92	
	58.4	93	
	58.8	94	
	59	95	
	59.2	96	
	59.5	97	
	59.8	98	
	60	99	
	60.2	100	
	62.8	110	
	65.2	120	
	67.6	130	
	68.7	135	
	70.1	140	
	70.5	145	
	72	150	295.5
	Change Temperature		
18 750	71.6	151	273
	71.7	152	
	71.8	153	
	71.8	154	
	71.8	155	
	71.8	156	
	71.8	158	
	71.9	160	
	72	170	
	72.1	180	
	72.2	190	
	72.4	200	
	72.7	210	
	72.8	220	
	73	230	
	73.1	240	
	73.2	255	273
	Change Temperature		
18 750	73.7	256	296
	74	257	
	74.2	259	
	74.5	260	
	75.2	265	
	76	270	
	77.3	280	

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPERATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
	78.9	290	
	80.2	300	
	81.8	310	
	86.9	345	
	87	345	
	87.3	349	
	87.4	350	296
	Change Temperature		
18 750	87	352	273
18 750	87.1	353	273
	87.2	365	
	87.3	395	
	87.9	424	
	88	450	
	88.2	480	
	88.4	500	273
	Temperature Change		
18 750	88.9	501	296
	89.1	504	
	89.2	506	
	89.6	508	
	90.3	510	
	93.4	515	
	94.8	520	
	96.4	530	
	97.5	540	
	98.5	550	
	99.5	560	
	100	565	296
	Temperature Change		
18 750	99.4	566	273
	99.7	567	
	99.7	571	
	99.8	580	
	99.8	590	
	99.9	610	
	104.2	1410	
	104.7	1493	
	104.8	1510	
	104.8	1530	273
	Change Temperature		
18 750	105.1	1531	296
	105.3	1532	
	105.4	1533	
	105.6	1534	
	105.9	1538	
	106	1540	
	106.9	1550	
	107.6	1560	
	108.3	1570	
	110.5	1600	
	112.4	1630	
	113.8	1700	
	114.2	1705	
	114.6	1710	
	114.9	1715	296
	Change Temperature		
18 750	114.7	1716	273
	114.5	1717	
	114.6	1718	
	114.7	1719	
	114.7	1725	
	114.8	1750	
	115.6	1950	
	115.7	1970	273
	Change Temperature		
18 750	116	1971	295
	116.1	1973	
	116.3	1975	
	116.8	1980	
	117.1	1985	
	117.5	1990	
	118	1995	

TABLE IV CONTINUED

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER-ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_1		t	T
20 850	54.6	2	296
	57.8	3	
	60.1	4	
	62.3	5	
	64.3	6	
	65.9	7	
	67.3	8	
	68.9	9	
	70	10	296
	Change Temperature		
20 850	70	11	273
	70.3	12	
	70.8	13	
	71	14	
	71.1	15	
	71.2	16	
	71.3	17	
	71.5	18	
	71.7	19	
	71.9	20	
	73	30	
	74	40	
	74.9	50	
	75.2	55	
	75.7	60	
	76	65	273
	Change Temperature		
20 850	76.5	66	296
	77.1	67	
	77.9	68	
	78.7	69	
	79.5	70	
	84.2	75	
	88	80	
	88.7	81	
	89.5	82	
	90	83	296
	Change Temperature		
20 850	89.8	84	273
	90	85	
	90.1	86	
	90.3	87	
	90.3	88	
	90.4	89	
	90.6	90	
	91	95	
	91.2	100	
	91.5	105	
	91.8	110	
	92	115	
	92.2	120	
	92.6	125	
	92.7	130	
	92.9	135	273
	Change Temperature		
20 850	93.1	136	296
	93.4	137	
	94.1	138	
	94.6	139	
	95.1	140	
	95.8	141	
	96.3	142	
	97	143	
	97.6	144	
	98.9	145	
	100.7	150	
	103	155	
	105.1	160	
	107.2	165	
	109.2	170	296

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER-ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_1		t	T
	Change Temperature		
20 850	108.8	171	273
	109	172	
	109.1	173	
	109.1	174	
	109.1	175	
	110.1	195	
	110.8	220	
	110.9	225	
	111	230	
	111.2	235	
	111.3	240	273
	Change Temperature		
20 850	111.9	241	296
	112.1	242	
	112.4	243	
	112.7	244	
	113.1	245	
	113.4	246	
	113.9	247	
	114.2	248	
	114.6	249	
	115	250	
	116.9	255	
	118.7	260	
	122.1	270	
	125.6	280	296
	Change Temperature		
20 850	125.1	281	273
	125.2	282	
	125.3	283	
	125.4	284	
	125.5	285	
	125.6	286	
	125.6	287	
	125.7	288	
	125.8	295	
	126	300	
	126.1	305	
	126.3	310	
	126.4	315	273
	Change Specimen		
22 900	67.9	1	295
	75.1	2	
	80.3	3	
	84.2	4	295
	Change Temperature		
22 900	85.1	5	273
	86.1	6	
	86.9	7	
	87.5	8	
	88	9	
	88.5	10	
	89	11	
	89.5	12	
	90	13	
	90.4	14	
	90.8	15	
	92.6	20	
	94.1	25	
	95.5	30	
	95.75	31	
	96.2	32	
	96.6	33	273
	Change Temperature		
22 900	97.2	34	295
	98.5	35	
	100	36	

TABLE IV CONTINUED

INITIAL STRESS P.S.I. σ_1	TOTAL GAGE READING 10^{-3} in	TOTAL TIME MIN. t	TEMPERATURE °K T
22 900	102.2	38	295
	104.7	39	
	107	40	
	109.5	41	
	112	42	
	114.2	43	
	116.7	44	
	119	45	
	121	46	295
	Changed Temperature		
22 900	121.6	47	273
	122.1	48	
	122.4	49	
	122.8	50	
	123	51	
	123.3	52	
	123.6	53	
	123.9	54	
	124.1	55	
	125.1	60	
	126.1	65	
	127	70	
	127.9	75	
	128.7	80	273
	Changed Temperature		
22 900	129.9	86	295
	131	87	
	132	88	
	133.1	89	
	135.1	90	
	136.9	91	
	138.9	92	
	140.5	93	
	Changed Specimen Changed Baths		
25 000	81	0.33	294.5
	85.4	0.5	
	90.4	0.66	
	94	0.833	
	97.4	1	294.5
	Changed Temperature		
25 000	104.2	2	273
	107.9	3	
	110.5	4	
	112.8	5	
	114.8	6	
	116.6	7	
	118.3	8	
	120	9	
	121.5	10	
	123	11	
	124.4	12	
	125.8	13	
	127.1	14	273
	Changed Temperature		
25 000	128.1	15	294.5
	131.2	16	
	136.5	17	
	145	18	
	150	19	294.5
	Changed Temperature		
25 000	149.9	20	273
	150.1	21	
	150.2	23	
	150.3	24	
	150.4	25	
	Changed Specimen		
20 850	41.1	1	273
	43.7	2	
	45.3	3	
	46.7	4	
	47.6	5	
	48.4	6	
	49.2	7	
	49.7	8	
	50.2	9	
	51	10	
	51.5	11	
	52	12	
	52.4	13	
	53	14	
	53.4	15	273
	Changed Temperature		
20 850	53.7	16	263
	54	17	
	54.1	18	
	54.3	19	
	54.5	20	
	54.7	21	
	54.9	22	
	55.1	23	
	55.2	24	
	55.3	25	
	56	30	
	57.4	40	
	58.5	50	
	59.3	60	
	60	70	
	60.9	80	
	61.7	90	
	62.2	100	
	62.7	105	
	63	110	
	63.2	115	
	63.8	120	264.5
	Changed Temperature		
20 850	63.9	121	273
	63.9	123	
	64	124	
	64.1	125	
	64.3	126	
	64.4	127	
	64.5	128	
	64.6	129	
	64.7	130	
	65.1	135	
	65.6	140	
	66.4	150	
	67	160	
	70.4	200	
	71.1	210	
	71.55	215	
	71.9	220	
	72.3	225	
	72.9	235	
	73.3	240	
	73.9	250	273
	Changed Temperature		
20 850	74.3	255	264.7
	74.4	258	
	74.5	260	
	74.8	265	
	74.9	266	
	74.9	267	
	75	270	
	75.2	280	

TABLE IV CONTINUED

INITIAL STRESS σ_i P.S.I.	TOTAL GAGE READING 10^{-3} in	TOTAL TIME t MIN.	TEMPERATURE T ^{o}K
20 850	75.6	290	264.7
	76	300	
	76.2	310	
	76.5	315	
	76.8	325	
	77.15	340	
	77.2	345	265
	Change Temperature		
20 850	77.6	348	273
	77.7	349	
	77.8	350	
	77.9	351	
	77.9	352	
	78	355	
	78.1	358	
	78.3	365	
	79	380	
	79.4	390	
	79.8	400	
	84.4	496	
	85.7	525	
	89.4	620	
	91.9	690	
	92.4	705	
	93	720	
	93.5	735	
	94	747	273
	Change Temperature		
20 850	94	748	265
	94.1	760	
	94.4	770	
	94.6	780	
	94.8	790	
	95	800	
	95.2	810	265
	Changed Specimen		
22 900	55.1	1	273
	58.5	2	
	60.6	3	
	62.2	4	
	63.7	5	
	64.9	6	
	66	7	
	67	8	
	67.9	9	
	68.8	10	
	69.7	11	
	70.4	12	
	71	13	
	71.9	14	273
	Changed Temperature		
22 900	72.6	15	263
	73.1	16	
	73.5	17	
	74	18	
	74.2	19	
	74.5	20	
	75.9	25	
	77.1	30	
	78.1	35	
	79.2	40	
	81.2	50	
	83	60	
	83.1	61	
	83.3	62	
	83.5	63	
	83.7	64	
	83.9	65	263.5
	Changed Temperature		
22 900	84.1	66	273
22 900	84.2	67	273
	84.6	68	
	85	69	
	85.1	70	
	85.2	71	
	85.5	72	
	86.2	75	
	87.5	80	
	89.7	90	
	90	91	
	90.1	92	
	90.3	93	
	90.7	94	
	91	95	273
	Changed Temperature		
22 900	91.1	96	263.5
	91.2	97	
	91.3	98	
	91.5	99	
	91.7	100	
	91.9	101	
	92	102	
	92.1	103	
	92.4	105	
	93.1	110	
	94.2	120	
	94.8	125	
	95	126	
	95.1	127	
	95.2	128	
	95.2	130	263.5
	Changed Temperature		
22 900	95.5	131	273
	95.8	132	
	96	133	
	96.1	134	
	96.2	135	
	96.4	136	
	96.6	137	
	96.9	138	
	97.2	140	
	98.1	145	
	99	150	
	100.8	160	
	102.3	170	
	104.1	180	
	107.3	200	
	107.9	205	
	108.8	210	
	109.2	213	273
	Changed Temperature		
22 900	109.5	214	264
	109.7	215	
	109.8	216	
	109.9	217	
	110	218	
	110.1	220	
	110.5	225	
	110.9	230	
	111.3	235	
	111.7	240	
	112	245	
	112.4	250	
	118.9	345	

TABLE IV CONTINUED

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER-ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_1		t	T
	Changed Specimen		
25 000	70.6	1	273
	75.9	2	
	79.4	3	
	82.5	4	
	85	5	
	87.3	6	273
	Changed Temperature		
25 000	89.1	7	267
	90.4	8	
	91.5	9	
	92.3	10	
	93.1	11	
	94	12	
	94.7	13	
	95.4	14	
	96.1	15	
	97.4	17	
	98.7	19	
	99.3	20	
	100	21	
	100.5	22	
	101.2	23	267
	Changed Temperature		
25 000	101.9	24	273
	102.6	25	
	103.5	26	
	104.3	27	
	105	28	
	105.7	29	
	106.5	30	
	107.9	32	
	108.7	33	
	109.4	34	
	110.2	35	
	110.9	36	
	113.7	40	
	114.4	41	
	115.1	42	273
	Changed Temperature		
25 000	116	43	267
	116.4	44	
	117	45	
	117.4	46	
	117.9	47	
	118.3	48	
	118.8	49	
	119.1	50	
	121.3	55	
	123.5	60	
	125.3	65	
	126.5	68	
	126.9	69	
	127.3	70	267
	Changed Temperature		
25 000	127.8	71	273
	128.3	72	
	128.9	73	
	129.3	74	
	129.9	75	
	130.3	76	
	130.9	77	
	132.6	80	
	135.3	85	
	138	90	
	139.2	92	
	139.9	93	
	140.6	94	
	141.9	95	273

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER-ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_1		t	T
	Changed Temperature		
25 000	141.9	96	267
	142.1	97	
	142.8	98	
	143.1	99	
	143.6	100	
	143.9	101	
	144.4	102	
	144.8	103	
	145.5	105	
	147.4	110	
	Changed Specimen Changed Baths		
22 900	50.6	1	246.2
	54	2	
	56.3	3	
	58.1	4	
	59.4	5	
	60.6	6	
	61.8	7	
	62.8	8	
	63.8	9	
	64.8	10	246.2
	Changed Temperature		
22 900	65	11	232.7
	65.2	12	
	65.3	13	
	65.5	14	
	65.6	15	
	65.7	16	
	65.9	19	
	66	20	
	66.3	25	
	66.6	30	
	66.9	35	
	67.1	40	
	67.4	45	
	67.7	50	
	68	55	232.7
	Changed Temperature		
22 900	68.3	56	246.2
	68.4	57	
	68.7	58	
	68.9	59	
	69	60	
	69.2	61	
	69.8	63	
	70.2	65	
	71.4	70	
	73.8	80	
	74.9	85	
	76.05	90	
	77.2	95	
	78.3	100	246.2
	Changed Temperature		
22 900	78.2	101	232.7
	78.4	102	
	78.5	103	
	78.5	105	
	78.7	110	
	78.9	115	
	79.2	125	
	79.5	135	
	79.8	145	
	79.9	150	
	80.1	155	
	80.2	160	232.7
	Changed Temperature		
22 900	80.6	161	246.2

TABLE IV CONTINUED

INITIAL STRESS P.S.I. σ_1	TOTAL GAG GAGE READING 10^{-3} in	TOTAL TIME MIN. t	TEMPER-ATURE °K T
22 900	80.7	162	246.2
	80.8	163	
	81	164	
	81.1	165	
	81.2	166	
	81.3	167	
	81.5	168	
	81.6	169	
	81.9	170	
	82.5	175	
	83.3	180	
	84.1	185	
	84.9	190	
	85.7	195	
	86.3	200	246.2
	Changed Temperature		
22 900	86.6	201	232.7
	86.7	202	
	86.7	203	
	86.8	204	
	86.8	205	
	86.9	210	
	87	215	
	87.1	220	
	87.3	225	232.7
	Changed Specimen		
25 000	59.3	1	241
	62.8	2	
	65.1	3	
	67	4	
	68.7	5	
	70	6	241
	Changed Temperature		
25 000	71.2	7	233.5
	71.8	8	
	72.2	9	
	72.7	10	
	73.1	11	
	73.4	12	
	73.8	13	
	74.2	14	
	74.5	15	
	76	20	
	76.3	21	
	76.7	22	
	77.1	23	223.5
	Changed Temperature		
25 000	77.6	24	241
	78.1	25	
	78.4	26	
	78.9	27	
	79.3	28	
	79.8	29	
	80.2	30	
	82.4	35	
	82.8	36	
	83.7	38	
	84.4	40	
	84.9	41	
	85.2	42	
	85.8	43	241
	Changed Temperature		
25 000	86.1	44	234
	86.3	45	
	86.7	46	
	86.9	47	
	87	48	
	87.3	50	
	87.8	52	

INITIAL STRESS P.S.I. σ_1	TOTAL GAGE READING 10^{-3} in	TOTAL TIME MIN. t	TEMPER-ATURE °K T
25 000	88.4	55	234
	89	60	
	90	65	
	90.6	70	
	91.8	78	
	93	88	
	93.7	93	
	94.3	98	
	94.9	103	234
	Changed Temperature		
25 000	95.1	104	241
	95.3	105	
	95.7	106	
	96	107	
	96.1	108	
	96.3	109	
	96.7	110	
	98	115	
	99.3	120	
	100.6	125	
	100.9	126	
	101.1	127	
	101.3	128	
	102.8	133	
	104.1	138	
	105.4	143	241
	Changed Temperature		
25 000	105.7	144	234
	105.8	145	
	106.	146	
	106.1	148	
	106.3	150	
	107.1	155	
	108.1	160	
	108.6	165	234
	Changed Specimen Changed Baths		
25 000	47.8	1	228
	49.2	2	
	50.1	3	
	50.8	4	
	51.3	5	
	51.8	6	
	52.1	7	
	52.6	8	
	52.9	9	
	53.2	10	
	53.4	11	
	53.6	12	
	54	13	228
	Changed Temperature		
25 000	53.7	14	218
	54.1	17	
	54.2	19	
	54.2	20	
	54.3	22	
	54.4	23	
	54.7	28	
	55	33	
	55.3	43	
	55.6	48	
	55.8	53	218
	Changed Temperature		
25 000	56.3	54	228
	56.3	58	
	56.6	60	
	56.8	61	
	56.9	62	
	57	63	
	57	64	

TABLE IV CONTINUED

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER_ ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_i		t	T
2 500	57.1	65	228
	57.8	73	
	58.6	83	
	59.2	93	
	59.8	103	228
	Changed Temperature		
25 000	57.7	104	218
	59.2	105	
	59.3	106	
	59.5	109	
	59.6	112	
	59.7	114	
	59.8	116	
	59.9	123	
	60	133	
	60.1	143	
	60.2	153	
	60.3	173	218
	Changed Temperature		
25 000	60.7	174	228
	60.8	175	
	60.8	179	
	60.9	183	
	61	193	
	61.1	203	
	61.3	213	
	61.6	223	
	61.8	228	
	61.9	233	228
	Changed Temperature		
25 000	62	234	218
	61.2	35	
	61.3	236	
	61.3	238	
	61.4	240	
	Changed Temperature		
27 100	62	80	195
	60.8	81	
	61	82	
	61.1	83	
	61.1	85	
	61.2	90	
	61.3	100	195
	Changed Specimen		
25 000	37	1	195
	38.5	5	
	39.2	10	
	39.5	15	
	39.9	20	
	40	21	
	40.8	24	195
	Changed Temperature		
25 000	41.2	25	218
	41.6	26	
	42.1	27	
	42.6	28	
	43	29	
	43.2	30	
	44	32	
	44.6	35	
	45.4	40	
	46.1	45	
	46.6	50	
	47.2	60	
	47.5	64	
	48	69	218
	Changed Temperature		
25 000	46.2	70	195
	47	71	

INITIAL STRESS	TOTAL GAGE READING	TOTAL TIME	TEMPER- ATURE
P.S.I.	10^{-3} in	MIN.	^{o}K
σ_i		t	T
27 100	71.1	69	218
	71.2	70	
	71.3	71	
	71.4	75	
	71.5	77	
	71.6	79	
	71.9	85	
	72.3	95	
	72.8	105	
	73.2	115	
	73.7	125	
	74	135	
	74.3	140	
	74.3	141	
	74.4	142	
	74.5	144	
	74.7	145	218
	Changed Temperature		
27 100	75	146	228
	75.1	148	
	75.2	149	
	75.3	150	
	75.4	151	
	75.5	152	
	75.6	153	
	75.7	154	
	75.8	155	
	76.3	160	
	76.8	165	
	77.2	170	
	77.7	175	
	7[illegible].1	180	
	78.7	185	
	79	190	
	79.6	195	
25 000	47.1	72	195
	47.2	73	
	47.3	74	
	47.3	75	
	47.4	84	
	47.4	94	
	47.4	104	
	47.4	114	195
	Changed Temperature		
25 000	48	115	218
	48.1	124	
	48.2	129	
	48.3	134	
	48.5	139	
	48.6	144	
	48.8	149	
	49	154	
	49.1	159	
	49.2	164	
	49.4	169	

TABLE IV CONTINUED

INITIAL STRESS P.S.I. σ_i	TOTAL GAGE READING 10^{-3} in	TOTAL TIME MIN. t	TEMPERATURE ^oK T
	61.5	263	218
	Changed Specimen		
27 100	63.5	10	218
	64.2	15	
	64.9	20	
	65.3	25	
	65.8	30	
	66.2	35	
	66.3	36	
	66.4	37	
	66.5	38	
	66.6	39	218
	Changed Temperature		
27 100	66.9	40	195
	67.2	41	
	67.3	42	
	67.6	43	
	67.8	44	
	68	45	
	68.2	46	
	68.4	47	
	68.6	48	
	69	50	
	69.8	55	
	70.4	60	
	70.5	61	
	70.7	62	
	70.8	63	
	70.9	64	195
	Changed Temperature		
27 100	71	65	218
	71	66	
	71	67	
	71.1	68	

INITIAL STRESS P.S.I. σ_i	TOTAL GAGE READING 10^{-3} in	TOTAL TIME MIN. t	TEMPERATURE ^oK T
	Changed Specimen Changed Baths		
27 100	51.5	1	218
	53.2	2	
	54.2	3	
	55.1	4	
	55.6	5	
	56.1	6	
	56.6	7	
	57	8	
	57.3	9	
	57.7	10	
	57.9	11	
	58.1	12	
	58.4	13	
	58.7	14	
	59	15	218
	Changed Temperature		
27 100	58	16	195
	58.1	17	
	58.2	18	
	58.3	20	
	58.4	23	
	58.5	25	
	58.7	30	
	57.7	50	195
	Changed Temperature		
27 100	59.7	51	218
	59.6	52	
	60	60	
	60.3	65	
	60.9	70	
	61.3	75	218

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